Bendix Navigation & Control Division

N69-39758

THE
BENDIX
CORPORATION

NAVIGATION AND
CONTROL DIVISION
TETERBORO, NEW JERSEY

FINAL REPORT
BENDIX OAO
STAR TRACKER PROGRAM

NAS 5-2108

REPORT NO.
7151-SS-69-4

PREPARED FOR:

NATIONAL AERONAUTICS
AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT
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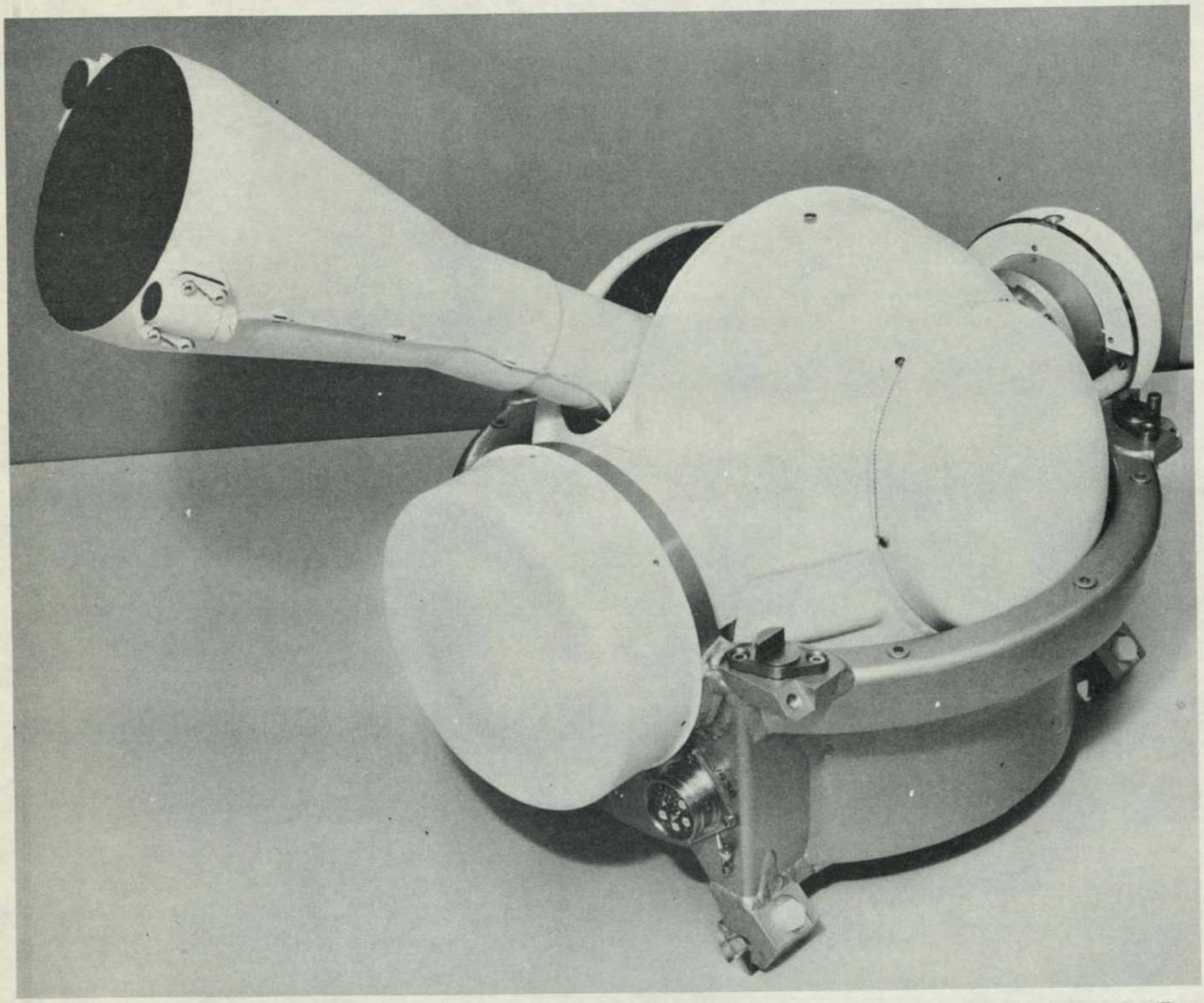


BENDIX OAO STAR TRACKER
FIGURE 1-1

1 0 INTRODUCTION

Bendix received a contract from NASA, Goddard Space Flight Center, to design, develop, fabricate and test a gimballed star tracker for the Orbiting Astronomical Observatory (OAO).

The program developed over four major periods of progress:

1. The initial design and development period;
2. The performance of a four and one half month qualification test program,
3. The period of investigation and redesign originated by the results of the qualification test program;
4. The final four and one half month qualification test program on the improved version of the Bendix star tracker. This qual test ended successfully on June 4, 1969 completing the Bendix OAO Star Tracker Program. (A separate set of documents, Report No. 7151-SS-69-1, containing a complete and detailed discussion of the Qualification Test Program has been written and transmitted to NASA.)

The contents of this final report represent a thorough discussion of the Bendix OAO Star Tracker Program. In addition to the present introductory remarks, the report is comprised of three major areas:

A. Technical Description
B. Historical Discussion
C. Recommended Design Improvements

Technical Description

This section contains a detailed description of the Bendix OAO Star Tracker System and upon reading this section, the reader will have a good understanding and physical picture of the Bendix OAO Star Tracker.

Historical Discussion

This section contains a complete and detailed history of the Bendix involvement in the NASA OAO Star Tracker Program. It shows the evolution of the Bendix OAO Star Tracker from the first day of contract go-ahead to the last day of the final qualification test program.

Recommended Design Improvements

This section discusses the areas of possible improvement to the Bendix OAO Star Tracker. The recommendations made are based upon the in-depth knowledge and practical experience gained by Bendix by participation in the NASA OAO Program.

SUMMARY OF BENDIX OAO STAR TRACKER CHARACTERISTICS

1.	System Accuracy:	22 arc seconds (one sigma) per axis
2.	Sensitivity:	+2.0 S-20 star magnitude or brighter
3.	Field of View:	± 1/2 degree
4.	Weight:	OMA = 25 lbs
		STE = 14 lbs
5.	Size:	OMA = 0.57 cu. ft.
		STE = 0.33 cu. ft.
6.	Power:	16 watts
7.	Detector:	ruggedized deflectable photomultiplier;
		S-20 photocathode
8.	Scan:	electronic cruciform
9.	Tracking Accuracy:	5 arc seconds at 1 deg/sec
10.	Torquers:	DC direct drive
11.	Rate Transducers:	DC tachometers
12.	Gimbal Position·	16 bit gray coded optical encoder
13.	Thermal Condition:	passive
14.	Available Readouts:	a) gimbal angles
		b) star presence
		c) track

The characteristics mentioned represent the major performance parameters of the Bendix OAO Star Tracker. An appreciation of the performance and environmental requirements of the star tracker can be attained by referral to the Grumman star tracker performance specification AV-252C3-72A and the Bendix final test report (7151-SS-69-1) previously mentioned. The Bendix OAO Star Tracker was qualified to the Grumman specification.

Throughout the contents of this report reference is made to various Bendix internal technical documents (prefixed with MT or TR). The reports have not been included as part of this documentation because they have already been transmitted to appropriate NASA personnel during the course of the OAO Program. However, copies will be made readily available if the need occurs.

2.0 TECHNICAL DESCRIPTION

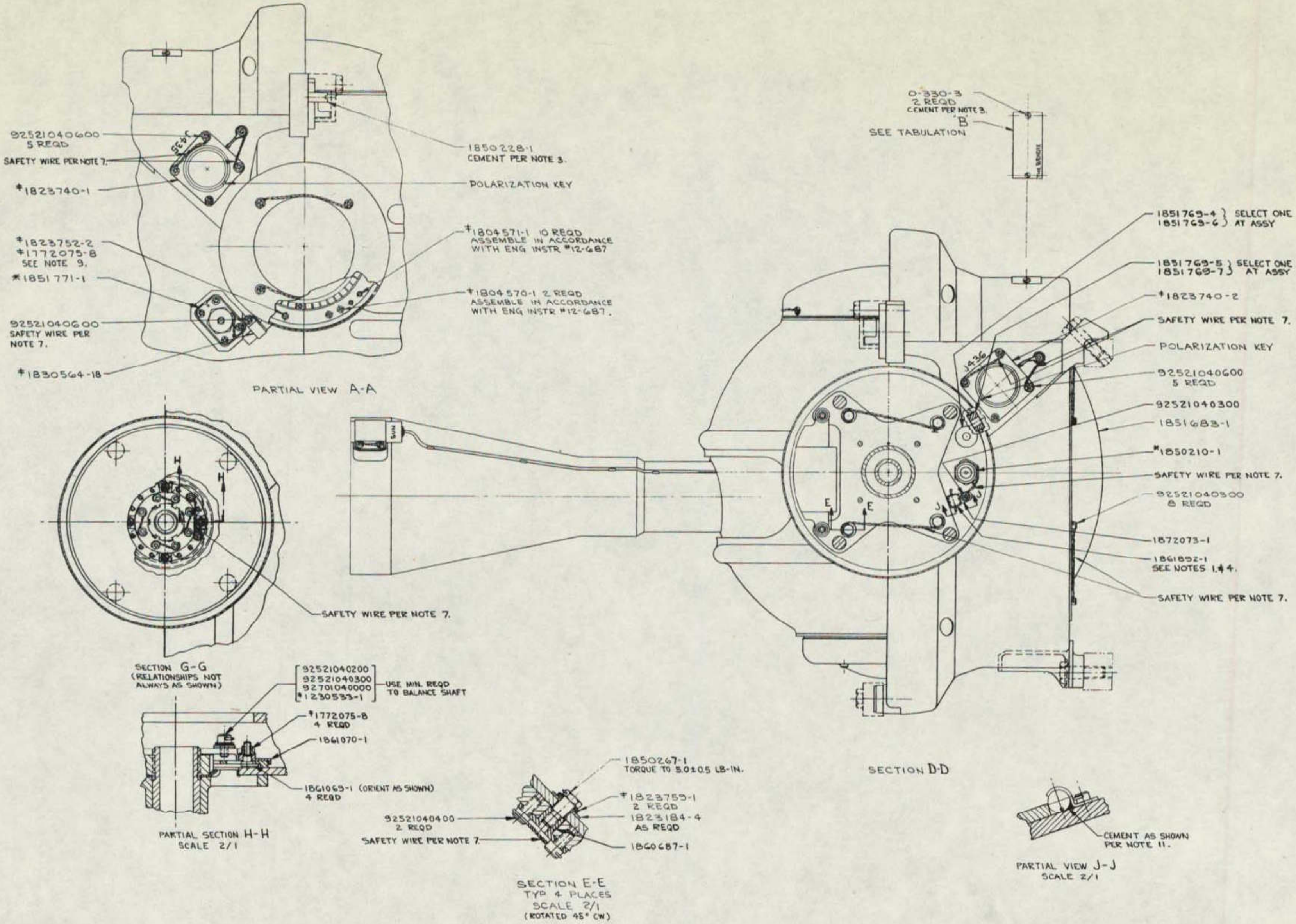
2.1 SCOPE

The purpose of this section is to explain the operation of the Bendix OAO Gimballed Star Tracker and provide the reader with a general description of the system as a whole.

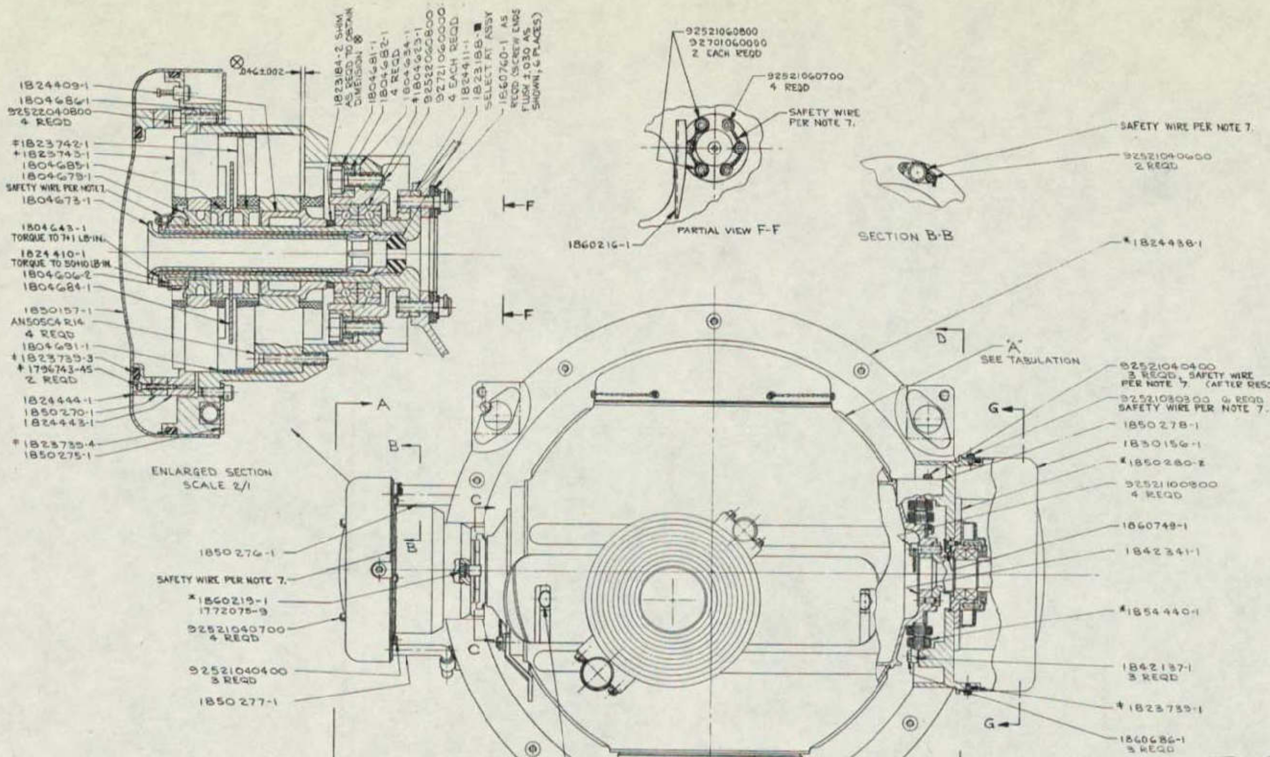
2.1.1 Optical Mechanical Assembly (OMA)

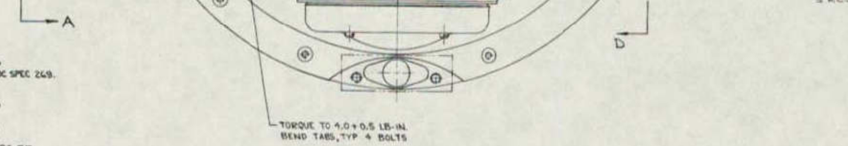
The star tracker assembly (Figures 2-1,-2)consists of a telescope supported by precision pitch and roll gimbals, each with $\pm 57^{\circ}$ authority. The telescope utilizes a refractive optics system of 1.42 inches clear aperture with an 8 inch focal length, focusing the star image on the photocathode of a deflectable photomultiplier. The multiplier phototube is electronically scanned and generates x and y coordinate error signals proportional to the angle between the telescope boresight axis and the star line. The gimbal drives are directly coupled DC torque motors. A 16 bit optical encoder mounted on each axis gives gimbal shaft angle position, while tachometers provide the required damping characteristics. There are two modes of tracker operation Track Mode and Command Mode.

In Track Mode operation, the target star is focused on the photocathode of the detector by the telescope optics. The detector is an image tube combined with a 16 stage photomultiplier. In this design, an aperture plate replaces the usual screen of the image tube. The aperture plate allows photoelectrons from a small area of the photocathode to be imaged on the first

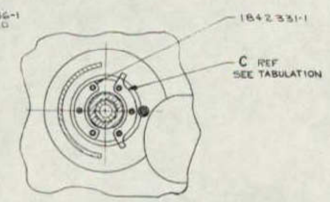


OAO OPTICAL MECHANICAL ASSEMBLY (OMA)
FIGURE 2-1





ELECTRICAL WIRES (SEE NOTE 1.)				
PART NO.	WIRE COLOR (REF)	AWG REF	FROM	TO
1860215-1	BRN-BLU	26	J435-22	OUTER MOTOR
1860215-2	BRN-VIO	26	J435-23	OUTER MOTOR
1860215-7	ORN-BLU	30	J435-17	OUTER TACH
1860215-8	ORN-VIO	30	J435-18	OUTER TACH
1850227-23	RED-BRN	32	J435-12	TB2-1
97001203005	BARE-WIRE	30	TB2-2	TB2-3
98414030■■■	RED	20	J435-31	TB2-2
98414040■■■	ORN	20	J435-32	TB2-4
97001203005	BARE WIRE	30	TB2-4	TB2-5
1850227-31	ORN-GY	30	J435-36	THRM TRANS
1850227-37	GRN-BLU	30	J435-37	THRM TRANS



SECTION C-C

NOTES:
1. WIRE IN ACCORDANCE WITH 1860999-1.
2. ASSEMBLE PER ENGINEERING INSTRUCTION 12-742.
3. CLEAN AREAS TO BE CEMENTED WITH XYLENE FOLLOWED BY FREON. DRY THOROUGHLY. THEN CEMENT PER E-P PROC SPEC 269.
4. SOFT SOLDER PER MIL-S-6872 USING SOLDER, COMP SN63, FORM W, TYPE AR, SPEC QQ-S-571.
5. OPTICAL CAVITY AND SENSORS TO BE KEPT COVERED AT ALL TIMES EXCEPT DURING TESTING.
6. HANDLE BEARINGS IN ACCORDANCE WITH ENGINEERING INSTRUCTION 12-729.
7. SAFETY WIRE PER MS33540 USING MS20995C20-■■ (LENGTHS AS REQD) LOCK WIRE.
8. MOUNTING SURFACES ARE EXTREMELY CRITICAL. PROTECTIVE SHOES MUST BE IN PLACE AT ALL TIMES EXCEPT DURING TESTING OR WHEN MOUNTED ON OTHER AUTHORIZED HANDLING FIXTURES.
9. SPOT FACE UNDER GROUND TERMINAL MUST BE CLEAN BARE METAL FOR GROUNDING PURPOSES.
10. UNLESS OTHERWISE SPECIFIED, ALL SCREWS MAY BE TORQUED IN ACCORDANCE WITH ECLIPSE-PIONEER STANDARD SHEET SS-118 USING 45T VALUES ONLY (14,500 PSI).
11. BEFORE ASSEMBLING COMPONENT CLAMP, CEMENT THERMAL RESISTOR TO ENCODER HOUSING WALL WHERE SHOWN, USING CONDUCTIVE EPOXY CEMENT (ROOM CURING) MADE BY EPOXY PRODUCTS INCORPORATED, THEIR SPECIFICATION # 3021.

OMA OUTLINE
FIGURE 2-2

multiplier stage. Deflection coils mounted about the image section of the tube deflect the image of the target across the aperture in a systematic sweep pattern. The detector output developed across a load impedance is a series of variable width pulses. When the target star does not lie along the optical axis, a difference in width of successive pulses gives rise to an error component at the fundamental sweep frequency. Synchronous gating circuits switch the detector output alternately to the x and y channels. The x and y signals with error modulation, are amplified and applied to phase sensitive detectors the outputs of which are DC signals with the amplitude representing the target star deviation from the optical axis and the polarity representing the direction of error.

The light sensitive element of the detector is protected from incident sun light by a highly reflective flag type shutter, that will interrupt the optical path when the telescope bore sight axis comes within 33° to 28° of the sun line. A sun sensor mounted on the sun shade acts as the solar detector. The solar cell in turn operates a rotary solenoid which positions the shutter in the optical path.

An earth sensor of similar design using a silcon cell operates the shutter for tube protection when the telescope bore sight axis comes within 10.5 $\pm$ 1.5 degrees of the earth line.

A resolver is mounted on the outer gimbal and produces sine and cosine components of the inner gimbal error referenced to the outer gimbal axis.

In the Command Mode the telescope may be positioned by externally generated signals to any discrete angle within 57 degree "square" gimbal authority. In each of the gimbal axes, an externally generated digital command is compared to the output of the 16 bit shaft angle encoder. The difference, or error, is externally converted into an analog signal which is fed to the DC torque motor. A continuous repetition of this process reduces the error to zero.

The telescope electronics generate a Star Presence signal when a star of suitable magnitude falls within the field of view.

2.1.2 Electronics Controller Assembly (STE)

The star tracker electronics controller assembly, Figures 2-3, -4, consists of the following:

1. Operational amplifiers and associated compensation networks.

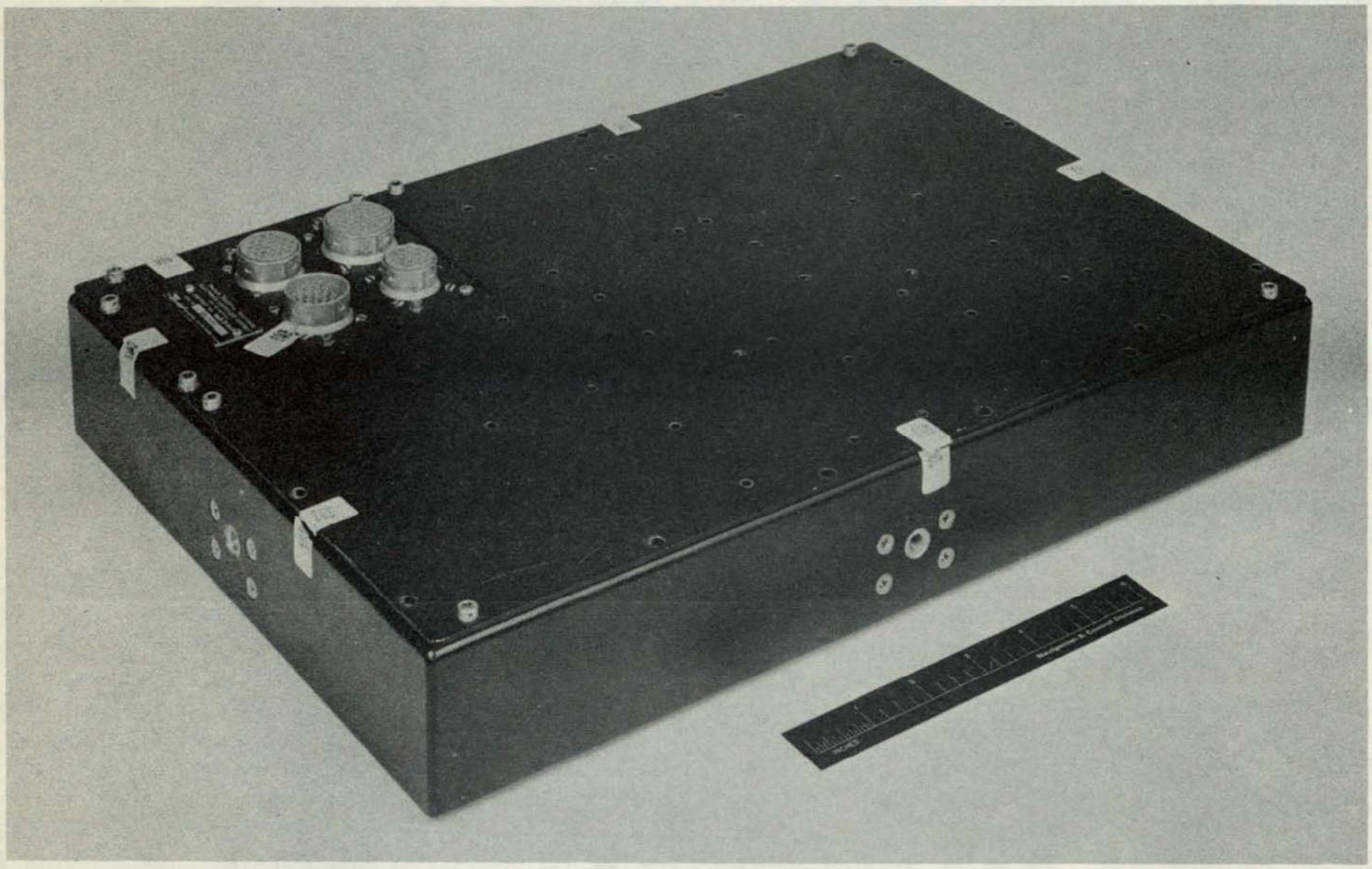
2. Power control and switching circuitry.

3. Telemetry circuits

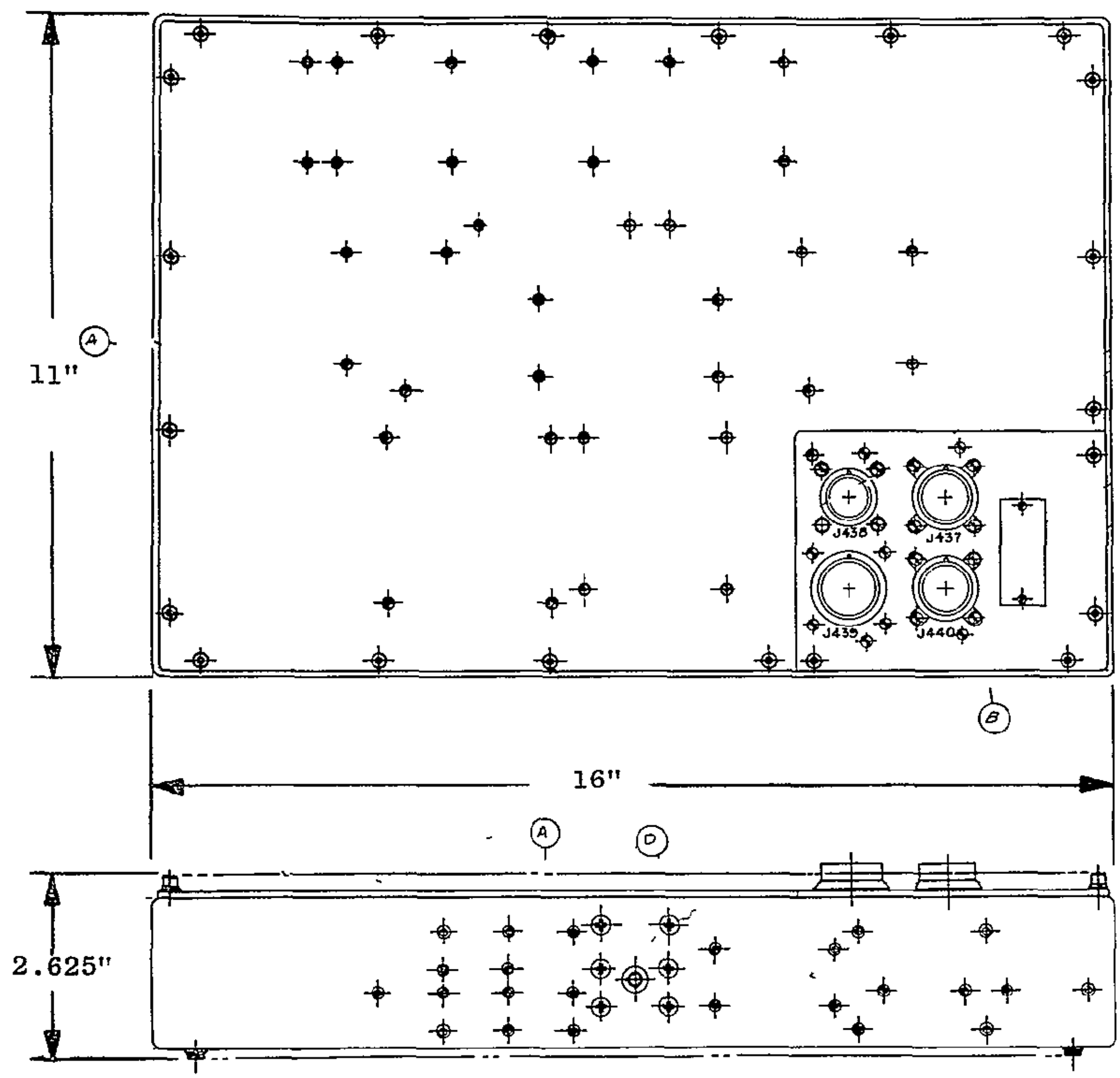
4. Encoder power supply

5. Detector circuits

6. Resolver circuit



OAO STAR TRACKER ELECTRONICS (STE) ASSEMBLY
FIGURE 2-3



STE
OUTLINE
FIGURE 2-4

7. Mode switch

8. Servo Interrupt Circuit

The star tracker electronics controller assembly, when properly excited, executes two prime functions.

a. It supplies the voltages required to operate the telescope and encoder electronics in the OMA.

b. It processes, depending on the mode of operation, either the DLU or OMA Star Input error signals, and then provides DC torque motors on the OMA gimbal axes with the driving voltages necessary to position the telescope to a desired orientation, utilizing the OMA tachometer output to provide error rate damping.

The STE also modulates the DLU inner gimbal error signal and sends the processed signal to the resolver mounted on the outer gimbal of the OMA. The resolver outputs, which are the sine and cosine components of the inner gimbal error referenced to the outer gimbal axis, are then returned to the STE where they are demodulated for use in the external system.

In the Command Mode the STE accepts the DLU inner and outer gimbal error signals, i.e. the difference between the actual gimbal angles as determined from the gimbal encoders and the commanded angles from the DLU, and generates the driving voltages to position the star tracker telescope to within one minute of the commanded position.

When a suitable magnitude star falls within the field of view of the telescope a Star Presence signal is generated, automatically switching the system to the Track Mode. In the Track Mode the STE accepts the inner and outer gimbal Star Input error signals from the telescope electronics and generates the driving voltages necessary to align the optical axis of the telescope with the target star. A star tracking signal will be generated by the STE when the vector sum of the Star Input errors is less than two arc-minutes.

2.2 MECHANICAL CONFIGURATION

2.2.1 Gimbal Support

The OMA consists of a refracting telescope subassembly supported in a double gimbal suspension. Direct drive DC torquers and tachometers and optical encoders are mounted on each axis. Both inner and outer gimbal axes incorporate precision ball bearings with labyrinth seals to protect components. Each end of the inner gimbal structure is supported on a duplex, angular contact, bearing pair with one end locked on both inner and outer races while the opposite end is permitted to float on the outer race, thereby minimizing thermal stresses. The locked bearing pair is an integral part of the 16 bit Optical Encoder. The outer gimbal structure is similarly supported on duplex, angular contact, bearing pairs, utilizing identical drive and readout components as used for the inner gimbal.

2.2.2 Gimbal Materials

The basic telescope housing is fabricated from Vanasil Z, a hyper-eutetic aluminum alloy. This material, although containing a large percentage of aluminum, has a coefficient of expansion below that of stainless steel and offers exceptional stability for optical devices while avoiding the toxicity and high cost of beryllium. Additional desirable characteristics of this alloy include low specific gravity, good thermal conductivity, good bearing properties, and excellent wear resistance.

The telescope subassembly is supported in a spherical welded structure of high strength aluminum, with appropriate slotting for telescope insertion and sun shade travel as well as mounting surfaces for the DC torquer, DC tachometer, and optical encoder.

The basic frame of this assembly is a welded structure of high strength aluminum consisting of a rigid, double walled, spin hemisphere with precision mounting pads and rings for receiving the DC torquer, DC tachometer and optical encoder.

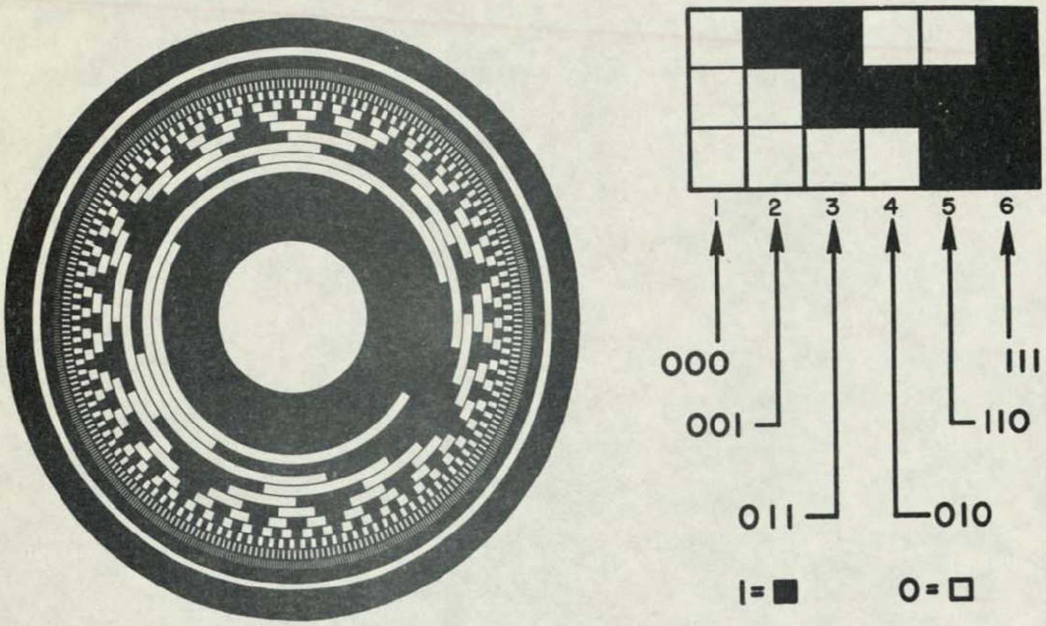
2.2.3 Motors and Tachometers

The combination consists of a torque motor and tachometer generator in a common housing completely shielded and mounted on precision bearings. The direct drive tachometers and motors eliminate gear backlash, thus assuring high servo position resolution. All materials contained in these units have low out gassing properties at a pressure of 10^{-6} mm of Hg. The important characteristics are:

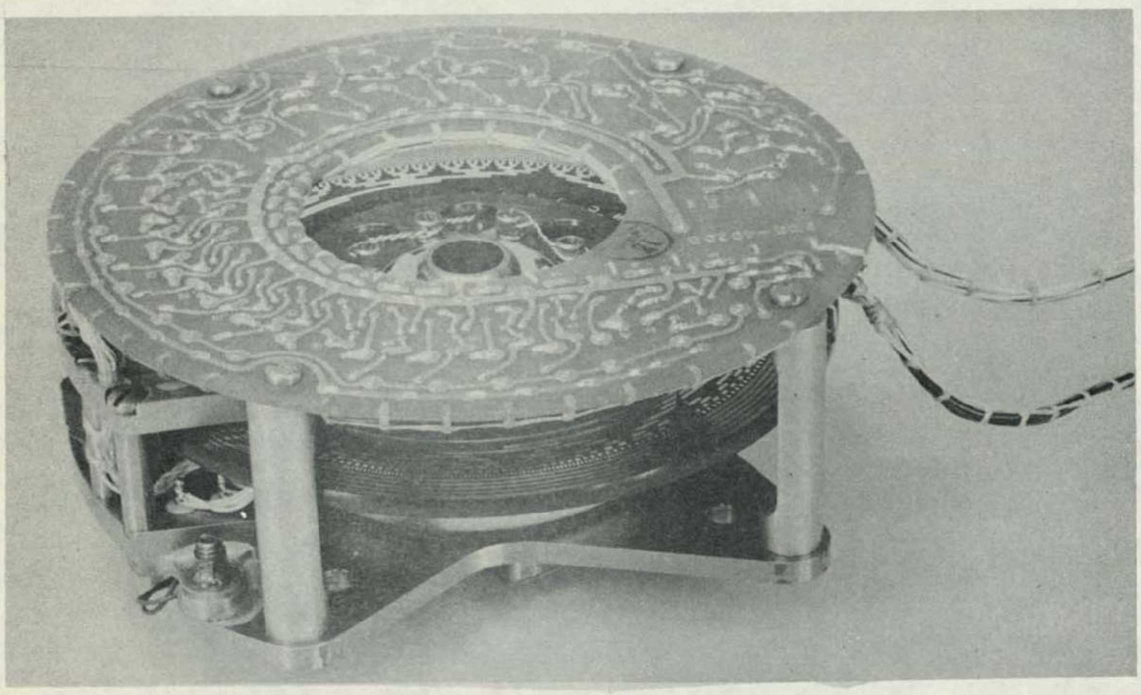
Motors:	Sensitivity	130-158 oz in/amp
	Friction	2.0 oz-in max
Tachometers:	Sensitivity	.72 - .88 volts/radian/second
	Friction	1.4 oz-in max

2.2.4 Gimbal Angle Encoders

The angular transducers for gimbal angle determination is a 16 bit optical encoder manufactured by Baldwin Electronics. These encoders provide the positions of the outer gimbal relative to the frame and the telescope inner gimbal, relative to the outer gimbal. This position information is supplied to the digital electronics in the form of 16 bit serial gray code. The digital electronics will convert it to serial binary and parallel binary for output to the vehicle and telemetry, respectively. This type of encoder uses a code disc with all of the position angles encoded directly (absolute). The code pattern consists of alternate transparent and opaque segments deposited in concentric annular rings as shown in Figure 2-5A.



GRAY CODED SHAFT ENCODER DISC
FIGURE 2-5A



OPTICAL ENCODER
FIGURE 2-5B

In operation, the code disc rotates relative to the frame. If a radial line on the frame is taken as a reference, the code pattern directly below the line describes a unique position. Actually, this radial line is a very narrow beam of light approximately 100 micro-inches wide impinging on the disc. Photocells are placed on the opposite side of the disc from the light beam, one under each concentric track. The position is determined by the ON-OFF state of the photocells which are dependent on whether the beam of light is impinging on an opaque or transparent section of the track. These low magnitude signals are amplified compared to a reference level, and then digitized. The composite 16 bit output represents a unique position of the axis relative to the frame.

2.2.4.1 Mechanical

A picture of the OAO encoder is shown in Figure 2-5B. The structural parts including mounting plate, shaft, and optical package are constructed of titanium for strength and thermal stability. The encoded disc is a polished plate glass encoded on one side by a photographic technique.

2.2.4.2 Electronics

The annular portion shown in the top of the picture contains the electronics including the 15 choppers feeding into a high gain amplifier, level detectors, and a monostable used to shape the output pulses.

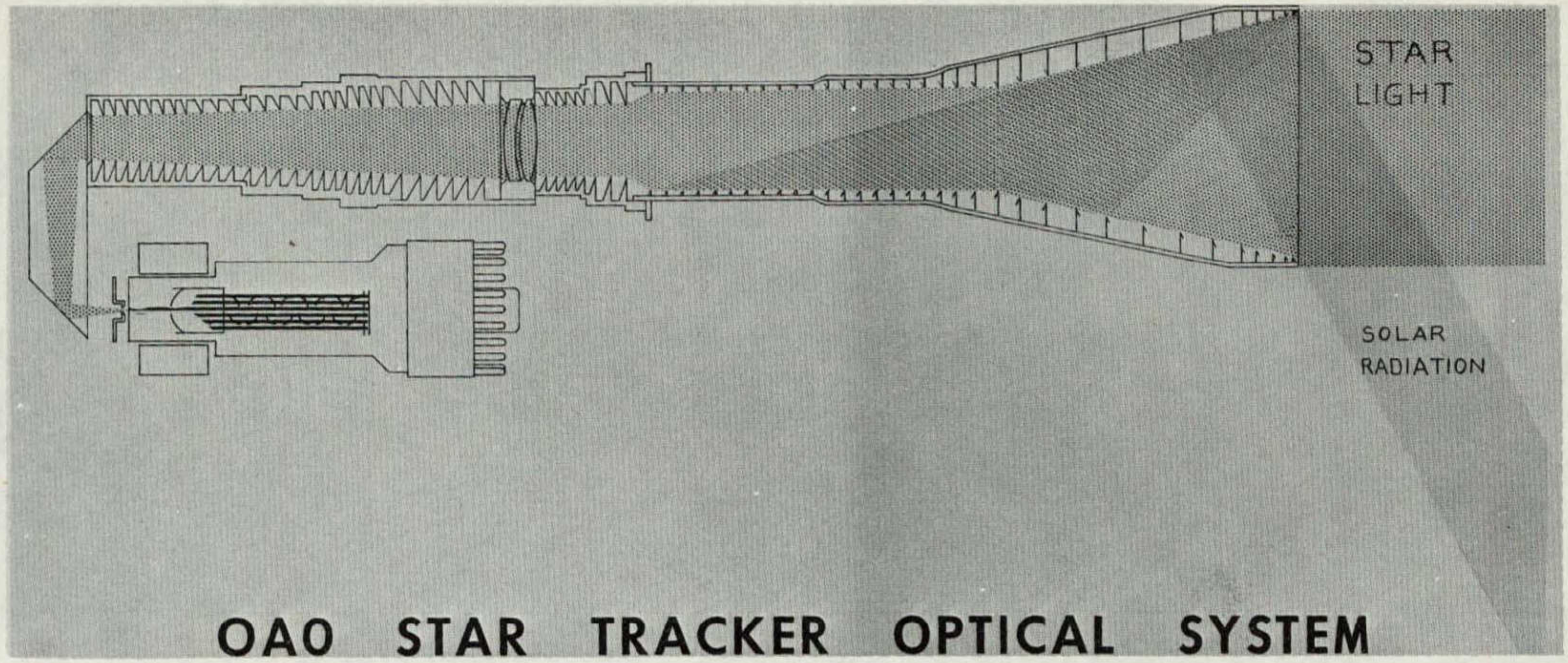
Only 15 choppers, corresponding to the least significant bits are required because the angular travel of the gimbals is less than 180^o. The major portion of the encoder electronics are time shared. This has the effect of reducing the power requirement and complexity of the encoder.

2.3 TELESCOPE ASSEMBLY

The basic transformation of star position information from visible radiation to electrical signals is performed within the Telescope Assembly. This would include the lens, prism, phototube, and associated signal processing electronics, with the sun shade performing a passive but important function. A full system description of these components follows.

2.3.1 Optical System

For star trackers the important subsystem, which initiates the performance of the tracker is the optical system. While the sun shade attenuates all oblique light, the optics collect radiant energy from the star and images the star onto the photosensitive surface of the deflectable photomultiplier. Figure 2-6 is a schematic of the optical subsystem. The optics of the Bendix star tracker system consists of an acromatic doublet and a fused quartz, truncated, right angle prism. The objective lens is a 6.833 inch focal length, F/4.6, aplanatic doublet. The major considerations taken into account in the lens design are good imagery in the spectral



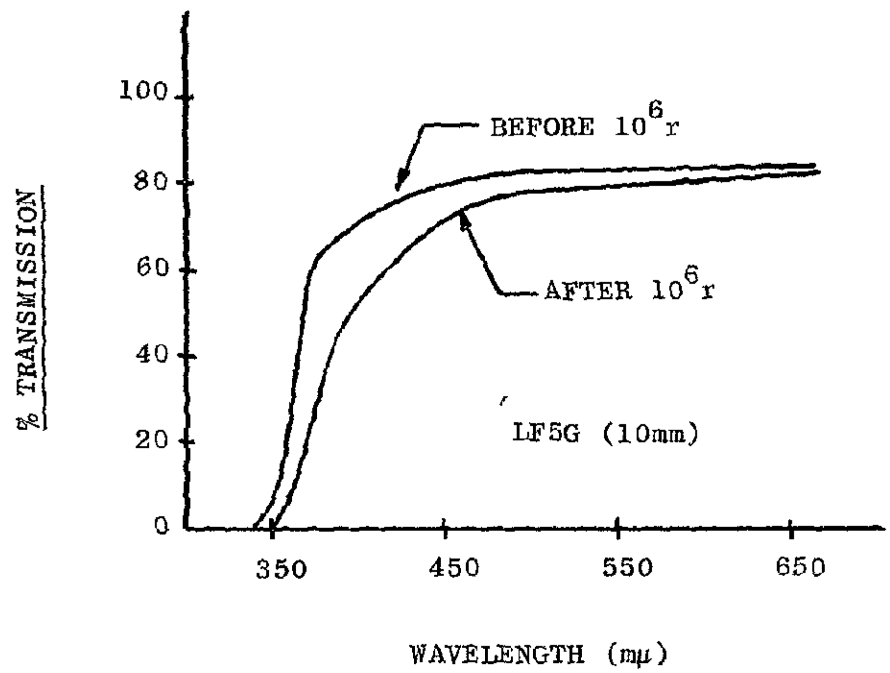
OAO STAR TRACKER OPTICAL SYSTEM
FIGURE 2-6

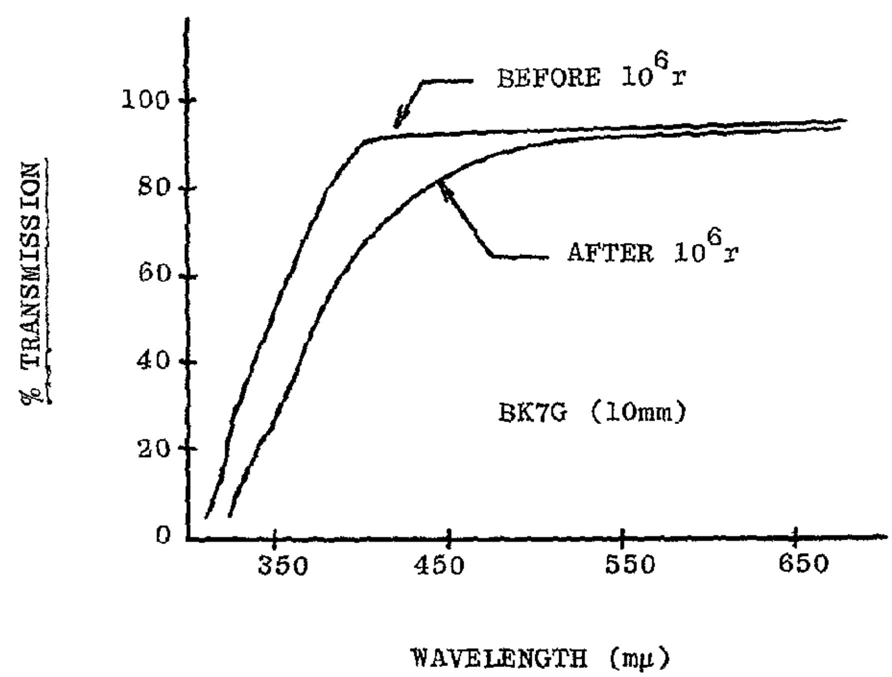
range from 365 Mμ to 800 Mμ, and the use of radiation protection (nonbrowning) glasses. The objective has a 1.500 inch clear aperture stopped to 1.42 inches by a baffle in order to attenuate stray light. The prism used with the objective is employed to fold the optical path, therefore, yielding a more compact telescope assembly.

The prism increases the distance from the center of the objective lens cell to the image plane, along the folded optical axis, by 1.12 inches. In the image plane of the optics, the star image blur circle is less than 0.002 inch diameter and contains approximately 80% of the star energy transmitted through the components.

2.3.1.1 Lens Design and Transmission Characteristics

The objective was designed to function with a prism that is used to fold the optical path. The front element of the objective is made of Schott BK7G, a boroscilicate crown glass doped with cerium oxide to provide radiation protection. An air space exists between the front element of the objective and the rear element. The rear element of the objective is made of Schott LF5G, a light flint also doped with cerium oxide. The transmission characteristics of the two glasses are given in Figure 2-7.





LENS ELEMENT RESISTANCE TO RADIATION
FIGURE 2-7

From the figure it can be seen that the transmission characteristics of the two glasses remain within 90% of the initial values after being subjected to radiation dosages of 10^6 rads. The prism, made of Corning U.V. 7940 fused silica is unaffected by similar radiation dosages

2.3.1.2 Stray Light Attenuation

An optical coating (Luxorb) is applied to areas of the prism and lens element edges which do not transmit or reflect the star light energy. This reduces off-axis stray light. Unless substantially attenuated, the stray light can, through multiple internal reflections, reach the detector and appear as extraneous noise.

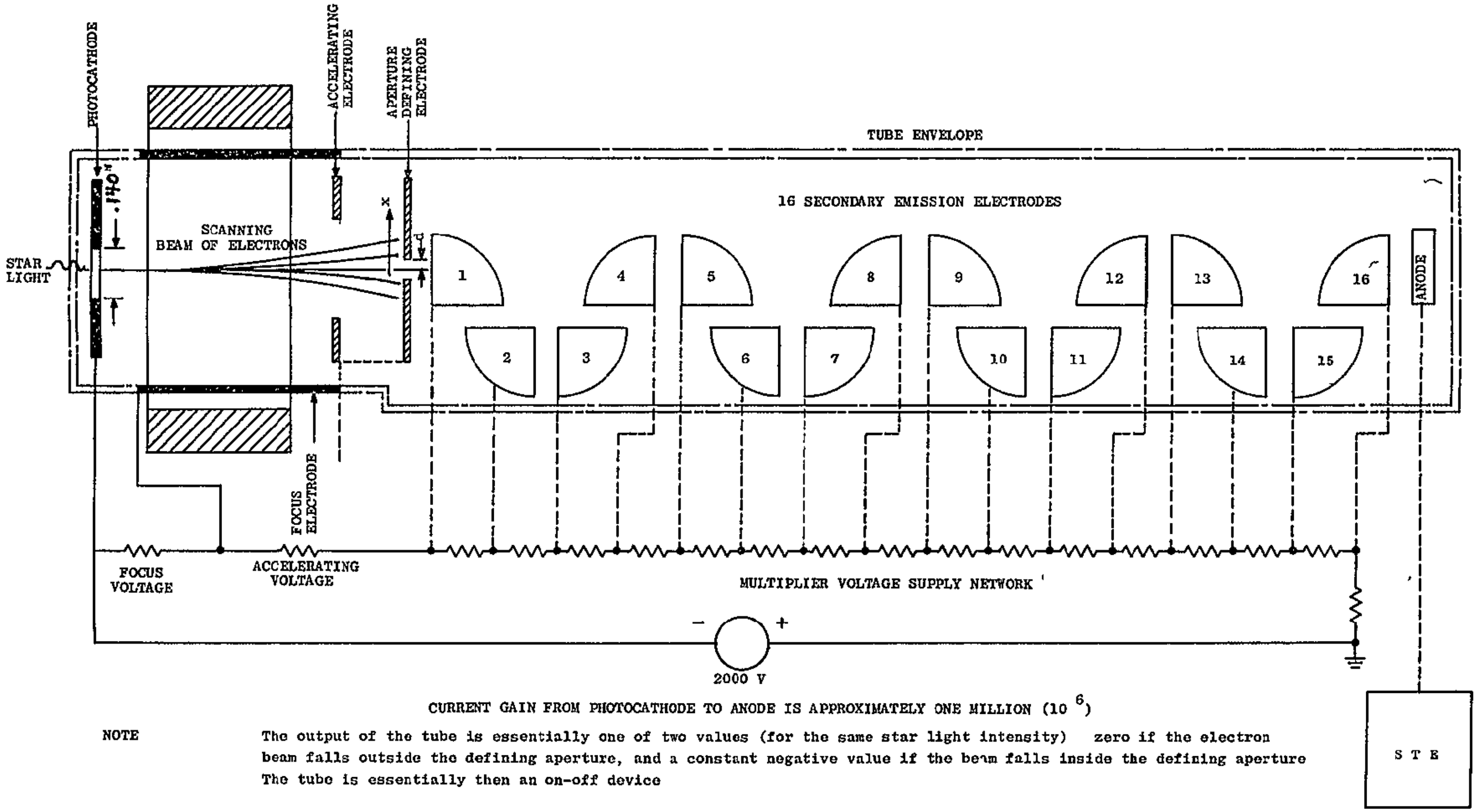
According to the Fresnel Equation of Reflection, light is reflected whenever it is incident on surfaces where there is a difference of optical index on both sides of the surface. The index of refraction of the Luxorb used is matched to the third decimal point to the glass on which it is applied. Therefore, reflection virtually does not occur at the glass-Luxorb interface, and the light is absorbed by dyes which are an ingredient of the Luxorb. Reflection attenuations on the order of 10^{-4} have been experimentally verified by tests performed at Bendix.

2.3.1.3 Lens Housing

The lens housing of the star tracker objective is made of beryllium. The housing is vented so that the air space can be bled-off, thus eliminating unnecessary stress upon the optical elements when the ambient becomes the hard vacuum of space. From thermal analysis it has been shown that the lens assembly will have a temperature excursion in space operation of slightly greater than 100°F.

2.3.2 Detector

The detector is the main system transducer which converts optical radiation from the star to a workable electronic signal. The Bendix system utilizes a deflectable photomultiplier as the detector. The optical information to electronic information conversion is accomplished by an external magnetic coil and the three main sections of the detector; the photocathode, the electron lens system (of which the aperture is an integral part) and the dynode multiplier. (See Figure 2-8). In operation, illumination from the star being tracked is imaged onto the photoemissive cathode driving off electrons which are accelerated toward the aperture. During this interval, two things occur. First, the electron lens system converges the electrons and focuses them onto an aperture located in the electrostatic image plane of the detector. Second, the external magnetic coil, mounted around this section, systematically deflects the



NOTE The output of the tube is essentially one of two values (for the same star light intensity) zero if the electron beam falls outside the defining aperture, and a constant negative value if the beam falls inside the defining aperture The tube is essentially then an on-off device

STAR TRACKER DETECTOR
FIGURE 2-8

electron image across the aperture. The electrons gaining entrance through the aperture are increased by dynode multiplication thus forming an "on" signal. The electrons which are swept onto the plate containing the aperture do not enter the multiplier, hence an "off" signal is produced during this interval. The information on the position of the star being tracked is contained in the wave train of the on-off pulses. It should be noted that this type of modulation scheme is all electronic and is devoid of moving parts, thus improving the reliability of the system.

The particular detector is an ITT FW-143 deflectable photomultiplier. This detector employs an S-20 (tri-alkali) photoemissive cathode. The S-20 was chosen because of its high quantum efficiency and low dark current. The cathode response in the blue end of the spectrum assists in providing a high efficiency for tracking blue stars such as the AO type stars.

The electrostatic lens system employed in the detector consists of a focusing ring deposited internally on the neck of the detector envelope and a circular aperture. The focusing potential is variable to provide for the best focusing voltage for each individual detector. The focusing feature increases resolution by reducing the size of the electron image that is deflected across the aperture.

In the plane of the electrostatic lens is a circular aperture of .140 inches diameter. Due to the geometry of th tube, the accelerating potential, and the focusing dynamics, the aperture is projected onto the photocathode with a magnification factor of 1.4. This area, and the optical focal length, 6.833 inches, produces an instantaneous field of view of 1 deg. The limited cathode area reduces the equivalent noise input by minimizing collected thermionic emission, while at the same time maintaining high collection efficiency.

Beyond the aperture is the multiplier section consisting of 16 dynodes, each of which exhibits secondary electron emission characteristics of approximately 2.5. The 16 stages thus produces an overall electron gain of approximately 2.3 million.

The anode, situated beyond the multiplier, collects the electrons and thus serves as the signal electrode.

Bendix has developed methods of optimizing tube performance for star tracking applications. A procedure of particular importance enables one to modify the tube output signal waveform before it enters the processing electronics. This method (called Dynode Shading) eliminates the change in error signal with changes in star illumination.

Dynode shading is accomplished by the judicious selection of the dynode potentials of the tube multiplier. Bendix has documented this subject in two reports; MT-13128, Issue A, "Wave-Shape Forming of a Deflectable Photomultiplier Used in Star Trackers" and TR-4063, "Null Stability as a Function of Shot Noise in a Cruciform Modulated Star Sensor".

2.3.3 Sensors

Bendix designed, developed, and fabricated for OAO use two types of sensors, for the purpose of providing the star tracker detector with protection from direct earth and sun illumination. Each type of sensor was individually designed to operate at specific sun and earth angles over a wide range of temperature variations to match their related trigger electronics.

In order to provide a redundant protective system for the star tracker, the sun and earth sensors each have separate trigger electronics and have the capability of reading to both the sun and the earth.

For calibrating and testing these sensors, Bendix has developed an earth albedo simulator and a $3000^{o}K$, two degree beam spread, tungsten sun that has an energy output equivalent to zero space sun.

2.3.3.1 Earth Sensor

The earth sensor is a photovoltaic device consisting of three voltaic cells arranged in such a way to achieve maximum sensitivity. This photovoltaic device is to provide a signal which will trigger when the angle of the optical axis to the earth's zenith is 12^{o} maximum. The reflected sunlight from the earth's albedo enters through an objective lens and produces an image of the earth's horizon. When the earth first comes into the field of view, the first cell becomes operative and yields a positive output. As the earth comes more and more into the field, the second and third cells provide an opposing negative signal to the first cell. The output of all three cells is voltaic and is fed into a high impedance circuit. Since the photovoltaic device is required to operate over a significantly large temperature range, a thermistor is used to adjust the sensor temperature coefficient to that of the related earth trigger. Figure 2-9 depicts the earth sensor output as a function of the angles from the earth's horizon.

Specifications for the earth sensor and trigger electronics are as follows:

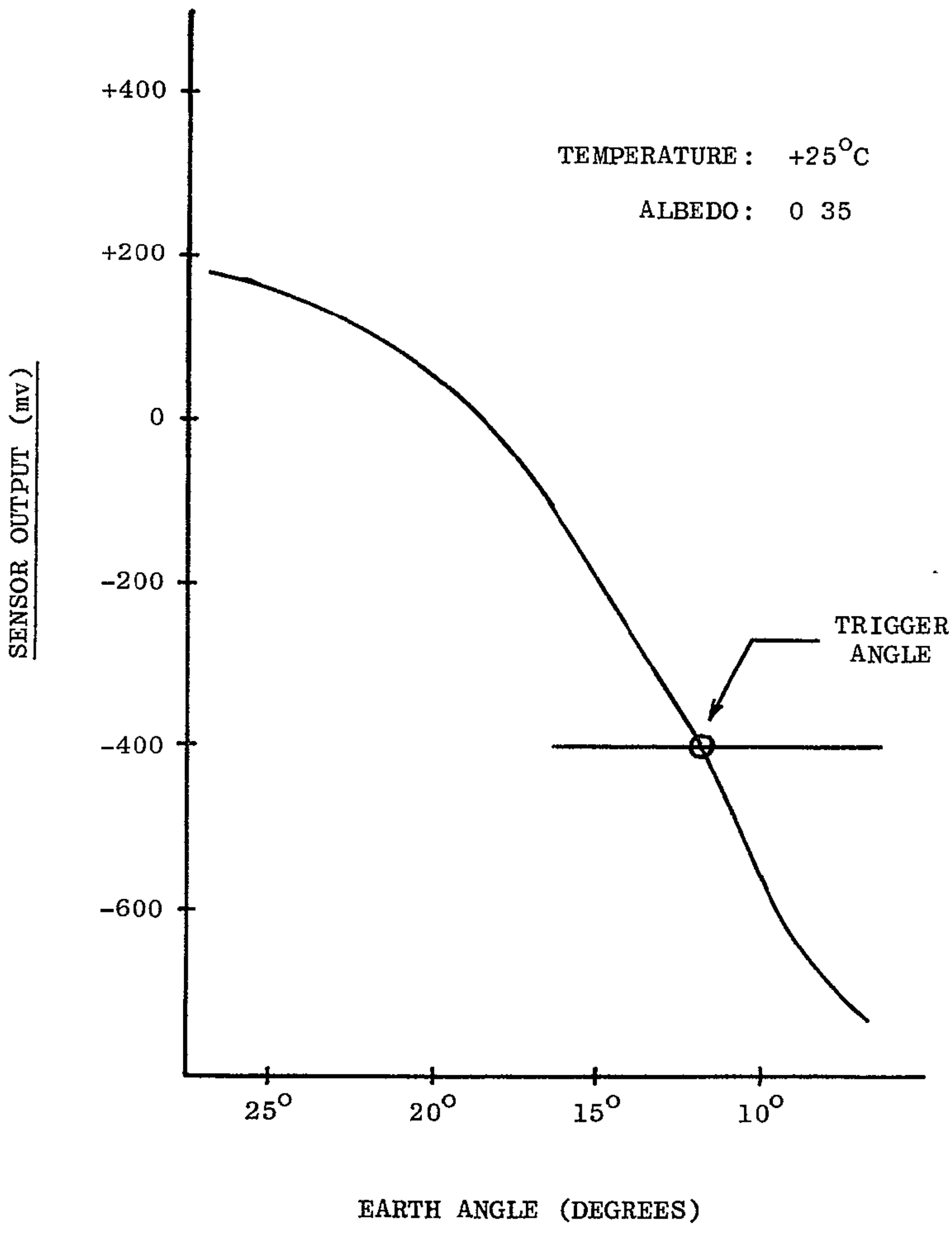
Temperature: $+37^{o}C$ to $-97^{o}C$

Rotational Symmetry: $\pm 1^{o}$

Sensor Output Voltage: -400 mv at $+25^{o}C$

Trigger Angle: $10.5^{o} \pm 1.5^{o}$ with .35 albedo

The earth sensor will not activate prematurely to the sun at an angle greater than 30^{o}.

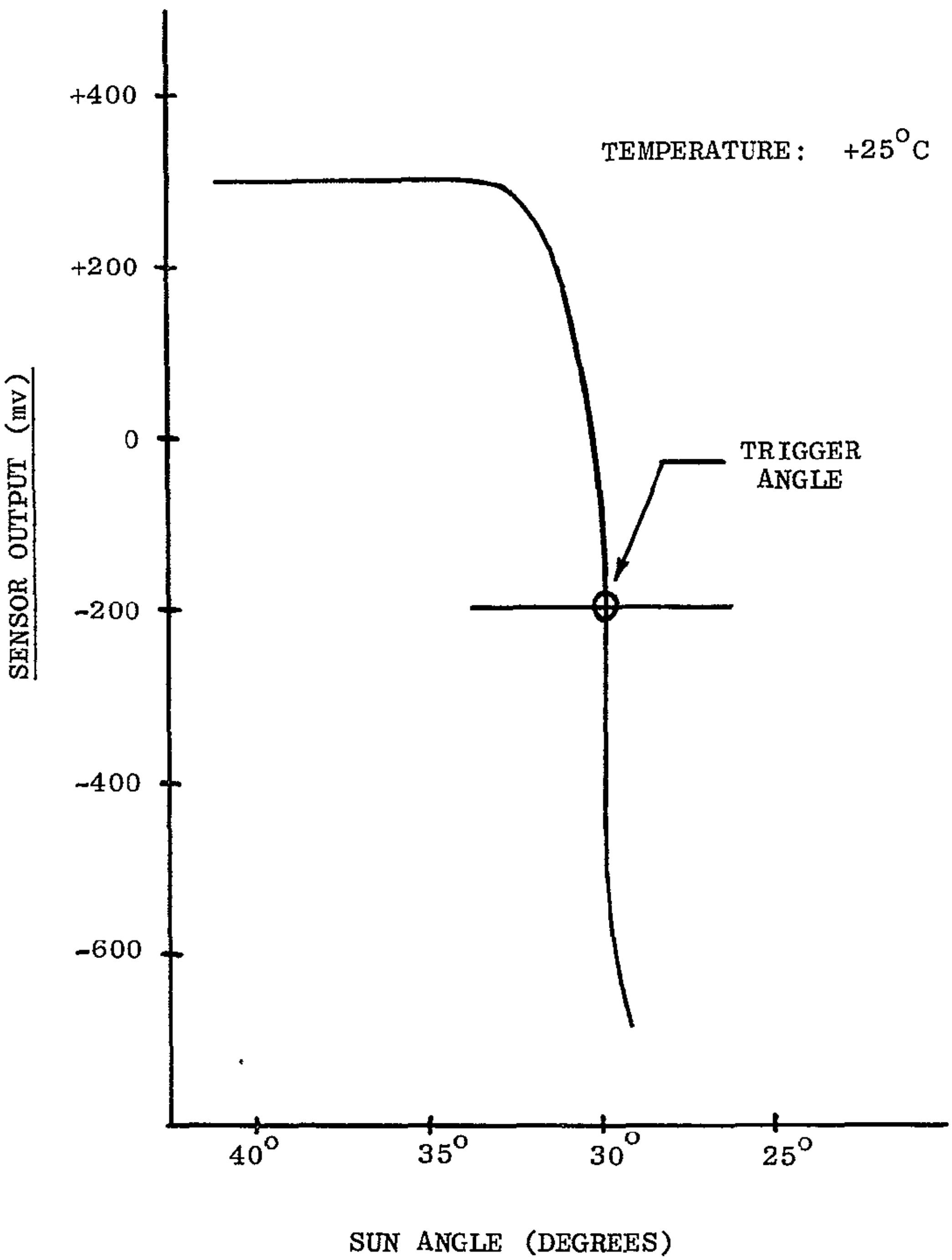


EARTH ALBEDO SENSOR CHARACTERISTICS
FIGURE 2-9

2.3.3.2 Sun Sensor

The sun sensor is identical in construction and operation to that of the earth sensor. Like the earth sensor it serves as a protective device. It protects the detector from damage when the angle between the sun rays and the optical axis is 30^{o}. A feature of the sun sensor is the use of an internal resistive network that prevents the sun sensor from activating prematurely against the earth at an angle greater than 12^{o}. Figure 2-10 shows the sensor output with respect to its sun angle.

Specifications for the sun sensor and related trigger electronics are as follows:
Temperature: $+37^{o}C$ to $-97^{o}C$
Rotational Symmetry: $\pm 1^{o}$
Sensor Output Voltage: -200 mv at $+25^{o}C$
Trigger Angle: 31^{o} $\pm 2^{o}$



SUN SENSOR CHARACTERISTICS
FIGURE 2-10

2.3.4 Sun Shade

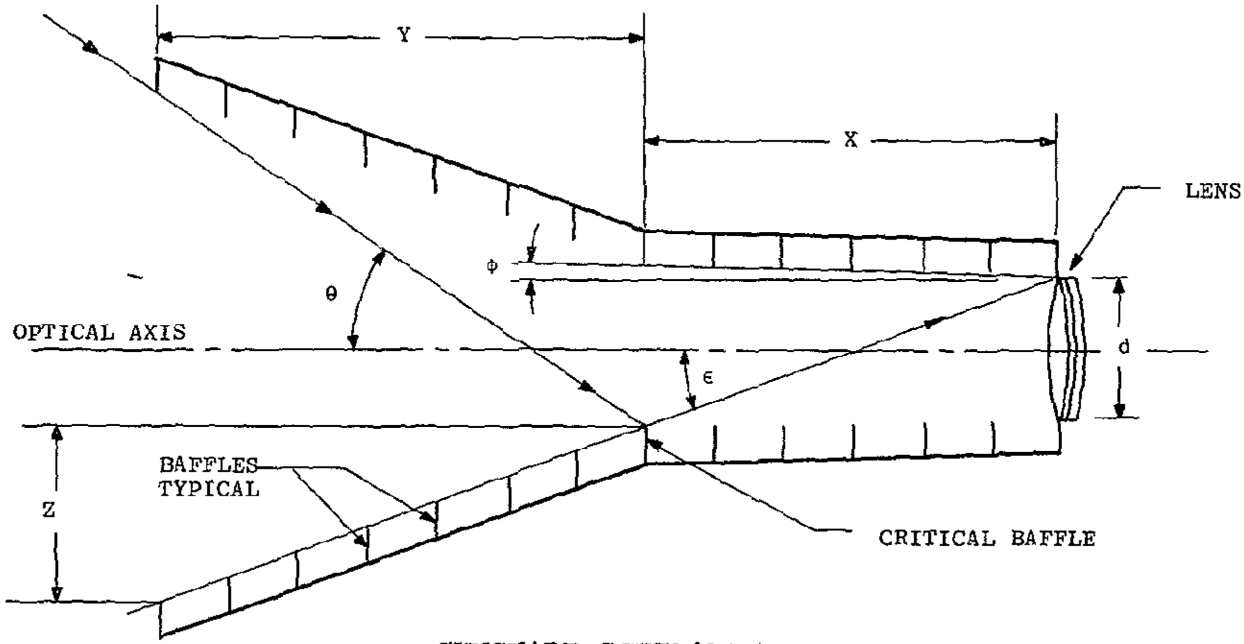
In order for the OAO Star Tracker to operate accurately at angles relatively close to the sun ($31^{\circ} \pm 2^{\circ}$) and/or the earth ($10\ 1/2^{\circ} \pm 1\ 1/2^{\circ}$), it was necessary to design a sun shield to effectively reduce the sun or earth intensity relative to a star.

The Bendix sun shade was constructed using thin metal baffles properly spaced from each other and embedded in fiberglass. The inside of the thin baffle was ground to a razor edge to further reduce reflections from the edge. The development of the construction techniques in themselves were extensive.

Important characteristics taken into account in the design are as follows:

1. The metal baffles must be sufficiently deep to require multiple reflections of the incident light before the light proceeds further down the shade.
2. Baffle edges must be sufficiently sharp to minimize secondary reflections directly down the shade.
3. The shade interior is coated with Parson's Black to reduce reflectivity to two (2) percent.
4. The mechanical structure of the shade is made of a relatively flexible material (Fiberglass) improving its ability to absorb vibration and shock.

An illustration of the type of schematic diagram used to initially evaluate the Bendix OAO Star Tracker sun shade parameters is pictured in Figure 2-11



SUNSHADE SCHEMATIC

FIGURE 2-11

In this schematic:

Θ = the minimum angle to the sun to which it is necessary to track

2ϕ = field of view of the optical system

d = aperture size of the objective lens

ϵ = the taper angle of the bell shaped portion of the shade

These parameters are used to evaluate the necessary data needed for the shade construction.

2.3.4.1 Generalized Shade Equation

From the figure one can write the following equations:

$$\frac{x}{d + x \tan \Phi} = \frac{y}{z} \quad \text{and} \quad \tan \Theta = \frac{d + 2x \tan \Theta + z}{y}$$

Combining these equations yields:

$$Y = \frac{xd + 2x^2 \tan \Phi}{x \tan \Theta - d - x \tan \Phi}$$

This general equation can be used to solve for any variable when the other three are known.

2.3.4.2 Minimum Shade Length

The minimum shade length can be found by solving for (X + Y), and then taking the derivative which is set equal to zero. This yields:

$$x = \frac{2d}{\tan \Theta - \tan \Phi}$$

Substitution into the general equation gives:

$$y = \frac{2d (\tan \Theta + 3 \tan \Phi)}{(\tan \Theta - \tan \Phi)}$$

Therefore, an expression for the minimum length is:

$$(x + y)_{min} = \frac{4d(\tan \Theta + \tan \phi)}{(\tan \Theta - \tan \phi)^2}$$

Using ($\Theta = 30^o$, $\phi = 1/2^o$, $d \leq 1.500$), yields a minimum length of 10.9 inches as an example.

2.3.4.3 Manufacturing Tolerances

Since tolerances must be included to manufacture a component, modification in the shade design must be made to allow for these tolerances. Therefore, the actual shade when combined with the shade mounting bracket has a length greater than the theoretical minimum.

2.3.4.4 Tracking to Earth

The earth is allowed to illuminate the cylinder portion of the shade directly since it is less intense than the sun, but it is not allowed to illuminate the lens. Therefore, the angle to which the tracker can track to the earth is:

$$\epsilon = \tan^{-1} \frac{d + x \tan \phi}{x}$$

2.3.5 Precision Optical Window

To prevent foreign particles from contaminating the star tracker telescope lens and sun shade interior during test, shipping and storage, Bendix has developed a removable, lightweight shade cover. This cover or precision optical window permits the tracker to function properly while mounted on the front aperture of the sunshade. The window material utilized on the OAO star tracker is Capran 77C, a transparent nylon -6- type thermoplastic film.

A technique was developed at Bendix to form the Capran into a 1/4 mil thick membrane with high optical transmittance and resolution.

In the development of a suitable window for the OAO sunshade, Bendix evaluated acrylic, quartz, and transparent plastic films with weight and optical quality the prime considerations. Capran was selected on its high rating in optical quality, low weight, durability, and adaptability to various sunshade parameters.

2.4 OUTPUT INFORMATION

The star tracker assembly, with its associated electronics and transducers converts angular positions into electrical signals, and provides four (4) pieces of information which are used to position the vehicle in space.

These four (4) pieces of information are:

Information Produced by Telescope Electronics

1. An error signal which is proportional to the angle (measured about the inner gimbal axis) between the telescope's optical axis and the star line.
2. An error signal which is proportional to the angle (measured about an axis orthogonal to the inner gimbal axis) between the telescope's optical axis and the star line. (Except for a gain error this is information of the star with respect to the outer gimbal axis, and hence shall hereafter be referred to as outer gimbal information.)

Information Produced by Encoders

3. The position of the star tracker inner gimbal with respect to the outer gimbal.
4. The position of the star tracker outer gimbal with respect to a vehicle.

The first two (2) pieces of information are used to keep the star tracker pointing at a selected reference star and may be thought of as being internal signals.

The second two (2) pieces of information are used to position the vehicle at some desired position with respect to the star trackers, while they inturn are locked onto their selected reference stars, and may be thought of as being external signals.

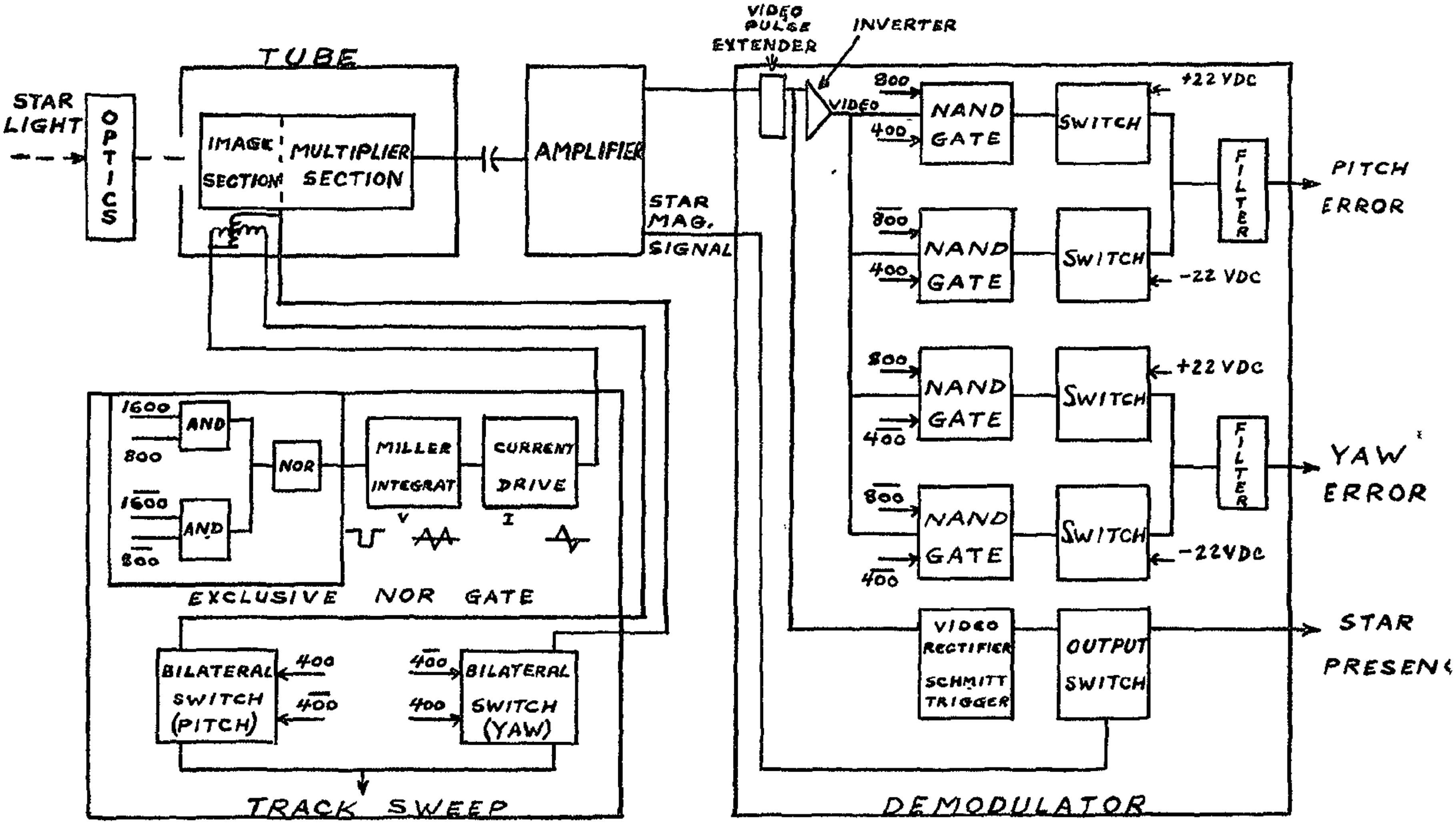
Because of the location of the star trackers on the vehicle, the external signals, produced by the encoders, provide information about the position of the tracker's gimbals with respect to the three (3) vehicle coordinates. These signals are averaged and produce a single set which is used to position the vehicle with respect to the trackers, and hence with respect to the stars being tracked. The inner gimbal information is transformed into the vehicle coordinates. The outer gimbal information is used directly, as the outer gimbal axis of each tracker is lined up with the vehicle control axis.

2.5 SIGNAL PROCESSING

2.5.1 Detector Information

By referring to the simplified block diagram of the star tracker telescope assembly Figure 2-12, the method of processing position information generated by the detector can be seen.

In the track sweep block, four (4) signals, 1600, $\overline{1600}$ pulses per second (PPS), 800 and $\overline{800}$ PPS, (obtained from binaries) is fed into logic blocks such that the 800 PPS signal in phase shifted by 90°. The 90° phase shifted 800 signal is then integrated and converted

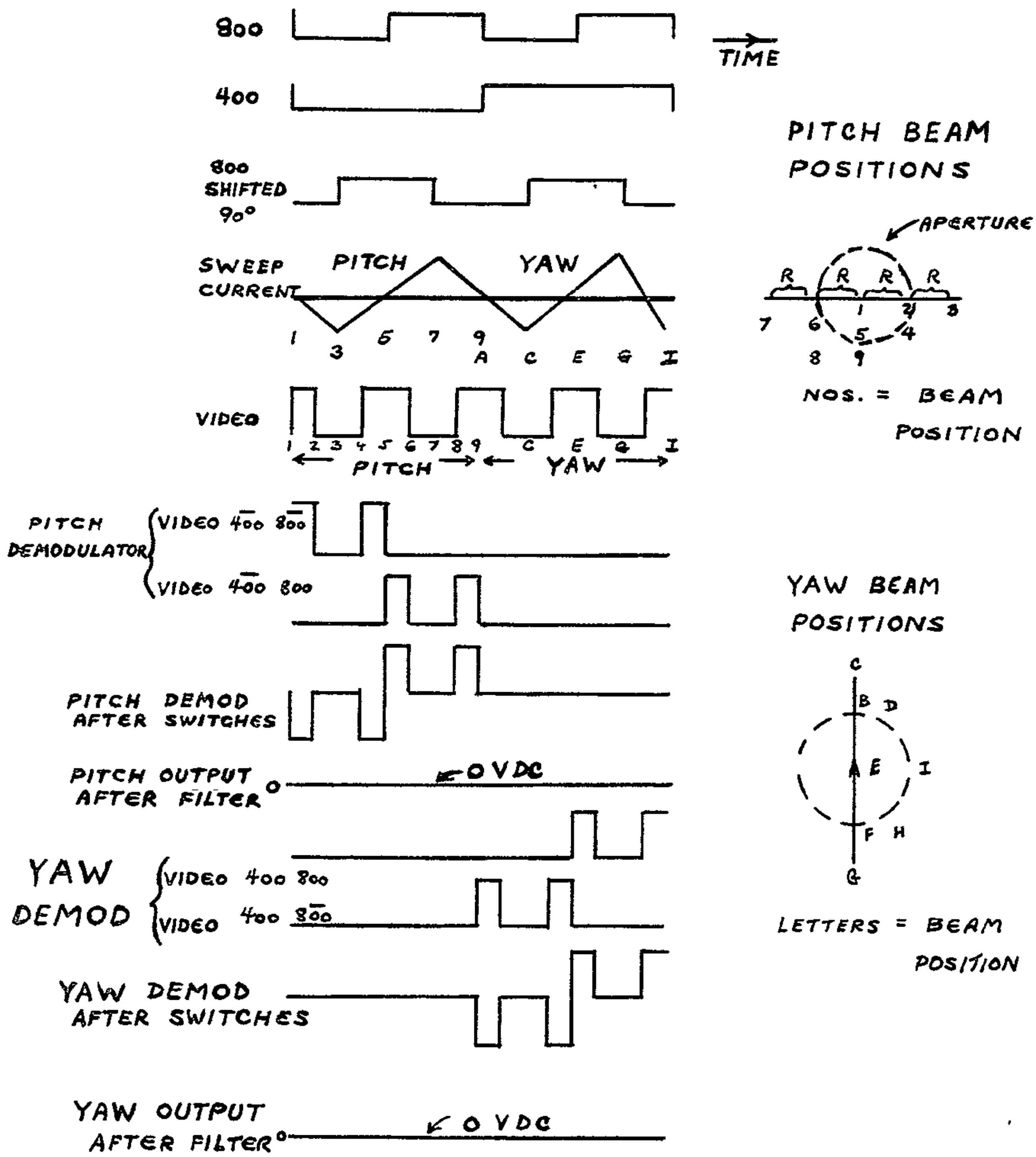


BLOCK DIAGRAM
TELESCOPE ASSEMBLY
FIGURE 2-12

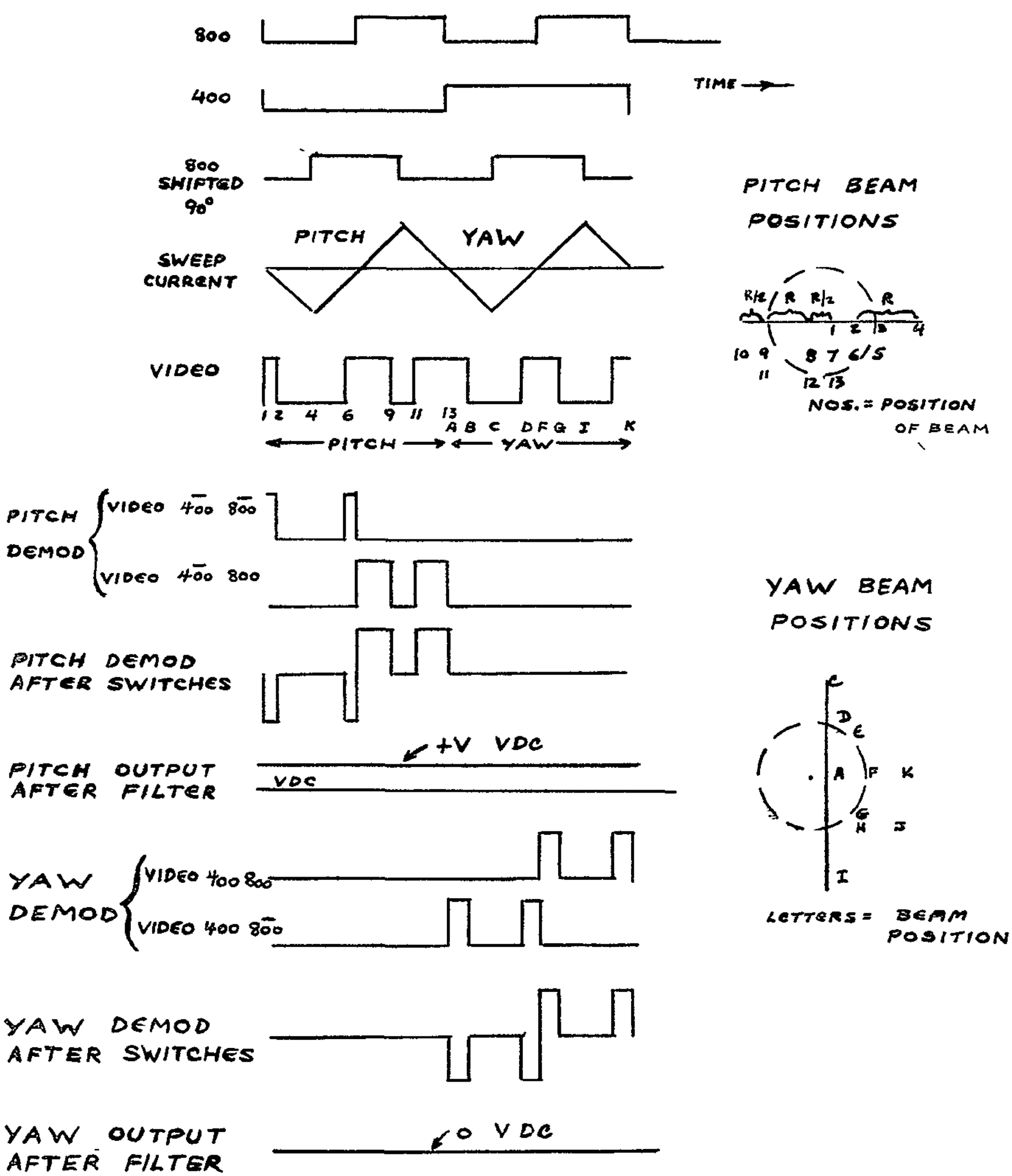
into a current wave-form which is fed to two sets of deflection coils. In the track sweep block there are also two (2) switches (activated by the 400 and $\overline{400}$ signals) which act to ground the two (2) deflection coils at the proper time. These switches are arranged such that only one deflection coil is activated at a time.

When a switch is closed the current sweep wave-form can pass through the appropriate coil causing the electron beam to sweep from its initial position either along an axis parallel to the inner gimbal axis of the star tracker, or an axis perpendicular to the inner gimbal axis of the star tracker. As the beam is swept across the aperture plate, it passes through the aperture at certain instants of time, and impinges upon the multiplier section of the tube. The multiplier section serves to amplify the weak signal by emitting secondary electrons from its dynodes. The output from the deflectable photomultiplier is a series of current pulses, which are amplified, changed to voltage pulses, and are fed into the demodulator. Logic circuits are now used to separate the inner gimbal information from the outer gimbal information. This information is then filtered, producing DC output signals, the polarity (+ or -) of which signifies the side of the axis for electron beam location and the magnitude of which signifies electron beam displacement from the optical axis center.

Two (2) sketches have been made which show the relationship between the various waveforms, Figures 2-13 and 2-14. The video signal is the signal which contains the beam position information. It is shown that for half a cycle of the 400 wave-form there is an entire cycle of inner or outer gimbal position information (referred to as pitch or yaw).



CENTERED BEAM
TELESCOPE ERROR SIGNALS
FIGURE 2-13



OFF-CENTERED BEAM
TELESCOPE ERROR SIGNALS
FIGURE 2-14

The number and letters which have been indicated show the beam position produced by the sweep waveform at different instants of time.

By using these various signals in the proper servo loop, it will be shown that the beam, and hence the star image, may be kept in the center of the star tracker optical axis, thereby effecting a tracking capability.

2.5.2 External Signal Information

The star tracker is mounted to two (2) sets of gimbals. Gimbal position information with respect to the vehicle (or the position of the vehicle with respect to these gimbals) is provided by the use of optical encoders. One encoder measures the angle between the outer gimbal and the vehicle. The second measures the angle between the inner gimbal and the outer gimbal. (This signal is later converted to information about the inner gimbal position with respect to the vehicle by means of a resolver and modulator, demodulator circuitry). The outputs from both encoders are digital in form.

In effect, the star tracker provides three (3) pieces of external information about the tracker postion with respect to the vehicle.

These three (3) pieces of information are:

External Signals:
- Outer Gimbal Error
- Inner Gimbal Error x sin outer Gimbal Error
- Inner Gimbal Error x cos outer Gimbal Error

The encoder signals from each star tracker are averaged, resulting in one final set of signals indicating the position of the vehicle with respect to three (3) coordinate axes.

Star Presence and Star Tracking Signals

When a star of proper magnitude appears in the field of view of the star tracker, a star presence signal is produced which is used to switch the tracker from the command to the track mode. The production of this signal may be seen on the simplified functional Block Diagram of the Telescope Assembly, Figure 2-12 .

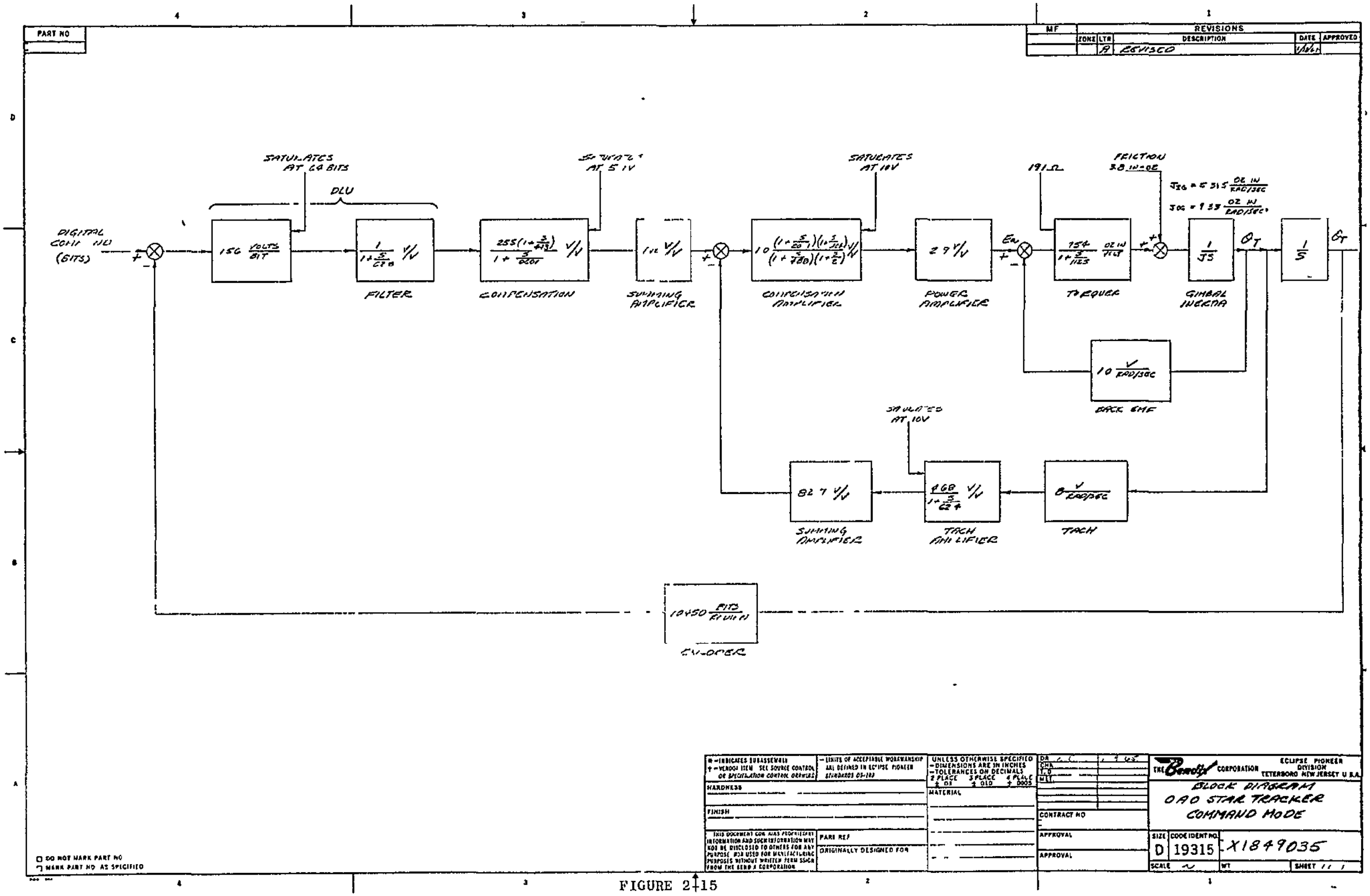
Star Tracking

When a star of proper magnitude is within two (2) arc minutes of the center of the field of view, a star tracking signal is produced.

2.6 DETAILED BLOCK DIAGRAMS

2.6.1 Command Mode

The detailed command mode block diagram Figure 2-15 shows that the output θ_t which is the angle between the vehicle and star tracker optical axis is compared to the desired position. The error signal produced goes to a compensation network (operational amplifier circuitry), introduced to eliminate noise produced by the phototube, and to provide loop stability. The output of the compensation is then compared to the output from a tachometer (also introduced for stability).



DIGITAL COMMAND (BITS)
SATURATES AT 64 BITS
DLU
FILTER
COMPENSATION
SATURATES AT 5 V
SUMMING AMPLIFIER
SATURATES AT 10V
COMPENSATION AMPLIFIER
POWER AMPLIFIER
191 Ω
FRICTION
TORQUER
GIMBAL INERTIA
BACK EMF
SATURATED AT 10V
SUMMING AMPLIFIER
TACH AMPLIFIER
TACH
ENCODER
REVISIONS
REVISED
BLOCK DIAGRAM OAO STAR TRACKER COMMAND MODE
THE Bendix CORPORATION ECLIPSE PIONEER DIVISION TETERBORO NEW JERSEY U.S.A.
D 19315 X1849035

FIGURE 2-15

This difference signal passes through another compensation network and serves to drive a DC torquer which is used to position the tracker with respect to the vehicle. This diagram applies to both the inner and outer gimbals of the star tracker, which differ only in the value of J.

2.6.2 Track Mode

The track mode diagram, Figure 2-16, shows that when θ_t (the angle between the vehicle and star tracker) is compared to θ_s (the angle between the vehicle and star) an error signal is produced, proportional to the angle of the tracker with respect to the star. This error passes through the star tracker telescope, (the block which was studied when the production of the two DC signals which indicated the location of the optical axis with respect to the star image was presented Figure 2-12), and then to compensation network. From this point on the circuitry is similar to that of the command mode.

2.6.3 Stability Study

A stability analysis was performed using the block diagrams for both the track and command modes. The results are presented below.

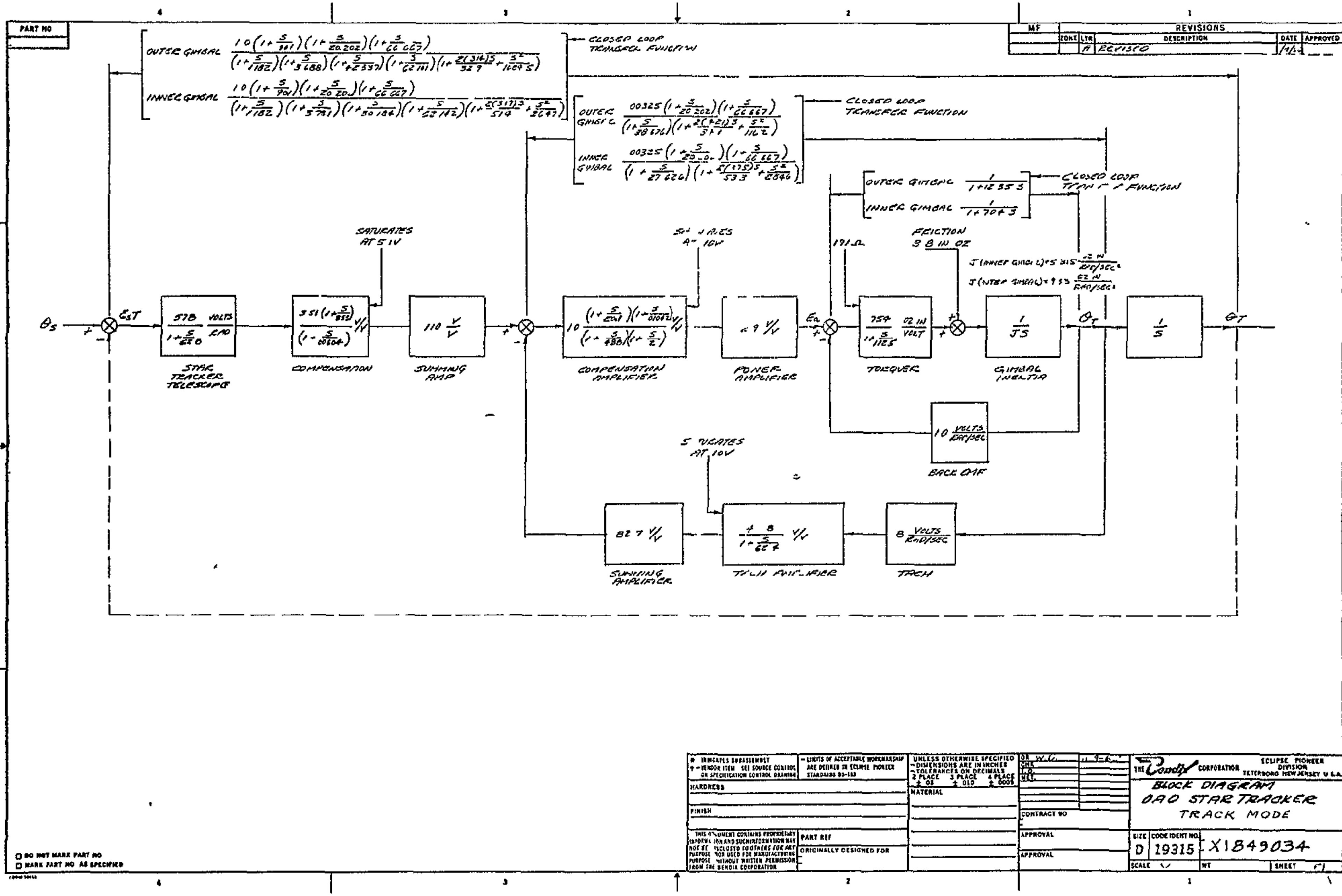
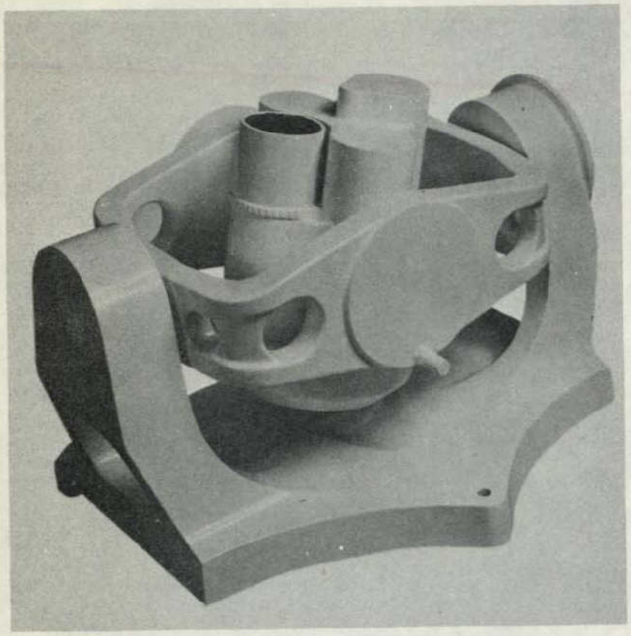

BLOCK DIAGRAM
OAO STAR TRACKER
TRACK MODE
STAR TRACKER TELESCOPE
COMPENSATION
SUMMING AMP
COMPENSATION AMPLIFIER
POWER AMPLIFIER
TORQUER
GIMBAL INERTIA
BACK EMF
SUMMING AMPLIFIER
TACH
SATURATES AT 5 IV
FRICTION
CLOSED LOOP TRANSFER FUNCTION
OUTER GIMBAL
INNER GIMBAL
D 19315 X1849034

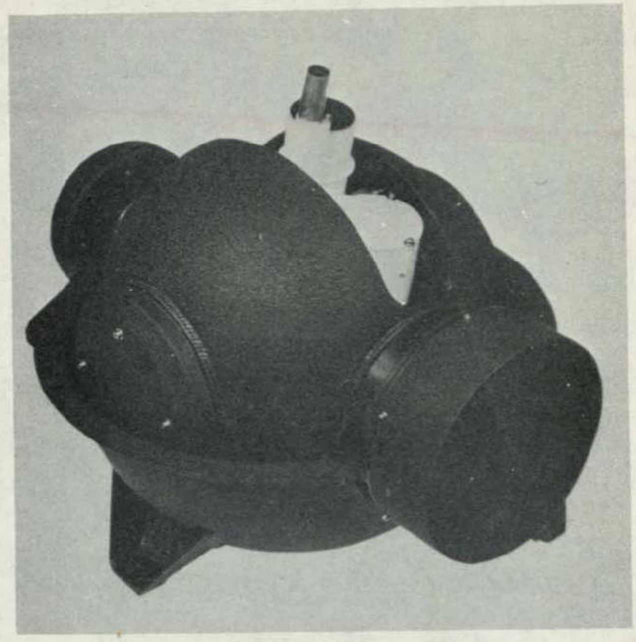
FIGURE 2-16

Because of the similarity of the results for the inner and outer gimbals, only outer gimbal data is presented.

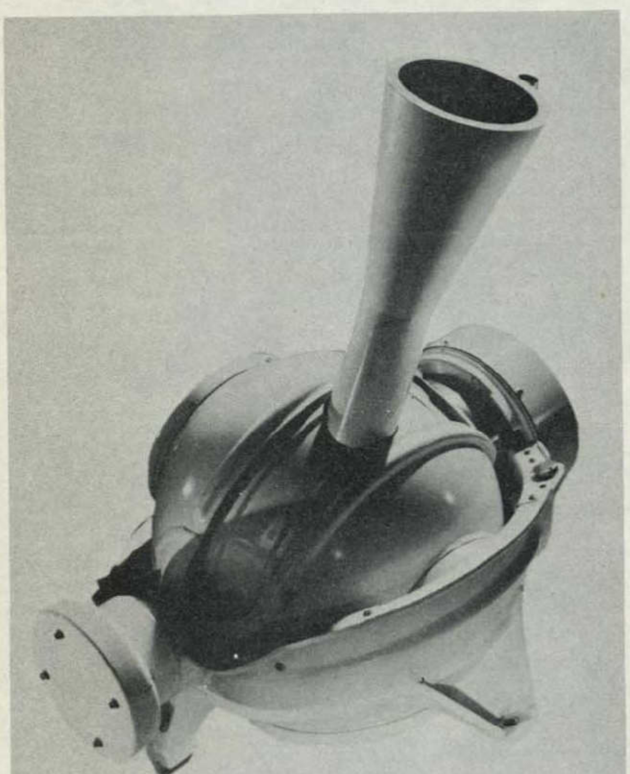
Mode	Rate Loop (Inner)	Position Loop (Outer)		
Star Track	Phase Margin 35°	Phase Margin 80°	Gain Margin 14DB	Bandwidth 1.1 cps
Command	35°	85°	10.5DB	4 cps



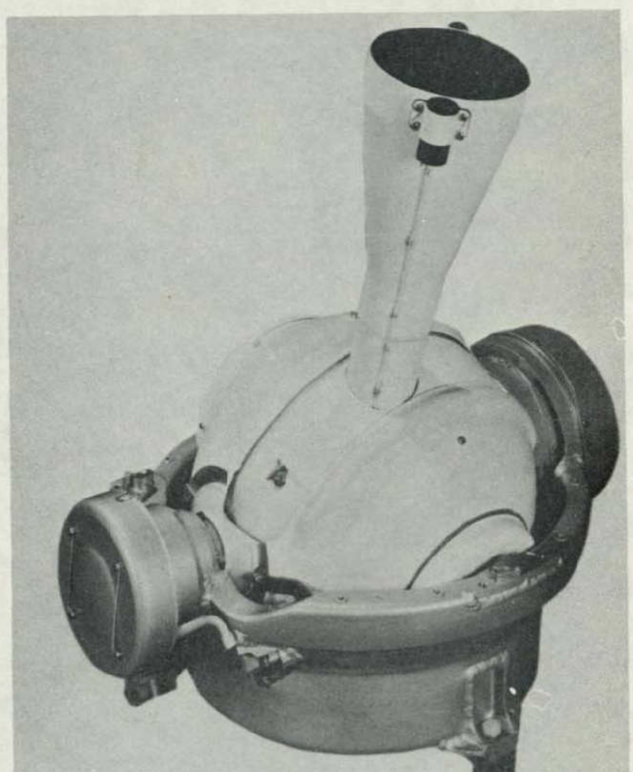
1962



1963



1964



1969

HISTORICAL DEVELOPMENT
BENDIX OAO STAR TRACKER
FIGURE 3-1

3.1 Part A-- Summaries and Highlights

YEAR - 1962

Summary

Bendix was awarded a contract in May from NASA, GSFC, to design, develop and fabricate one (1) Prototype Model Star Tracker and one (1) Qualification Model Star Tracker. The star tracker is comprised of an Optical Mechanical Assembly (OMA) and Electronics Assembly (STE). Upon fabrication, Bendix was to perform qualification tests and furnish the appropriate resulting data and documentation.

The application of the star tracker was for use in the Stabilization and Control Subsystem of the Orbiting Astronomical Observatory (OAO). The specification to which the star tracker had to perform is highlighted in another section of this report.

The Bendix accomplishments for this initial year of the program can, in general terms, be described by the following chart,

DESIGN EFFORT	75% Complete
FABRICATION EFFORT	25% Complete
TOTAL CONTRACTUAL REQUIREMENT	25% Complete

The effort for the present year involved the detailed analysis and definition of the star tracker design. Discussions with NASA were held to formulate interface requirements between the star tracker and OAO spacecraft, and fully define the various environmental considerations. The groundwork for a total effort was laid with the initiation of preliminary system block diagrams, circuital schematics, mechanical configuration drawings (OMA, telescope), and materials and parts descriptions.

A contract was awarded to ITT, San Fernando, for design, fabrication and delivery to Bendix of the telescope electronics (includes the detector and associated signal processing electronics) for the eventual incorporation into the OMA assembly. A majority of the circuits were designed, fabricated and functionally operated by the end of the year.

The encoder contract was awarded to AR and T Electronics (later known as Baldwin Electronics). The lamp and detector subassembly was completed by December. Torquers were ordered and received, while the resolver was fabricated and functionally tested. After extensive study, the decision was made as to the gimbal and frame configuration and preliminary fabrication began.

Preliminary design work on the Digital Logic Unit was initiated by Bendix and by the year end, the logic design was completed.

YEAR - 1962

HIGHLIGHTS

MAY-JUNE (1962) - NASA Contract Go-Ahead

ELECTRONICS

- Star Tracker - OAO Spacecraft interface discussions
- Preliminary OMA-STE block diagrams and schematics
- Contract with ITT, San Fernando, for telescope electonics

MECHANICAL

- Star Tracker - OAO Spacecraft interface discussions
- Preliminary design drawings for telescope housing

SYSTEM

- System definition studies
- Discussions with NASA on environmental considerations
- Preliminary analyses for servo loop and temperature distributions

JULY-DECEMBER (1962)

ELECTRONICS

- Encoder contract to AR and T Electronics (later Baldwin Electronics)
- Encoder lamp and detector assembly built and successfully tested
- ITT telescope electronic package design attains 95% completion
- ITT electronics potted in cylinders and functionally checked

- DLU preliminary circuit design started
- DLU logic design started and completed
- Breadboard design of OG servo loop and electronics started

MECHANICAL

- Star Tracker materials evaluation started
- Preliminary design of gimbal and frame configuration started; considerations given to box beam vs. spherical gimbal, and cast vs. welded metal fabrication
- Gimbal layout ultimately completed; decision for spherical IG and hemispherical OG with hydroformed welded construction
- Initial lens and prism elements received - chromatic aberration, problems with lens, new lens delivered from Ednalite Corp.
- Telescope housing with lens and prism shipped to ITT
- Mechanical interface discussions with ITT and AR and T
- Necessary mechanical parts for two (2) encoder assemblies shipped to AR and T
- Protective Shutter ordered from DACO
- Protective shutter undergoes thermal vacuum and vibration tests
- Excessive amplitudes with protective shutter vibration test leads to redesign,flag mass reduced; shaft heat treated
- Design of labyrinth seal configuration with vacuum tests
- DC torquer motors ordered and delivered
- Resolver fabricated and functionally checked

SYSTEM

- OG servo loop analysis completed - stability assured
- Servo analyses continue
- IG encoder temperature calculations performed
- Telescope housing temperature distribution studies
- Preliminary STE fabrication starts
- Gimbal structures fabricated and heat treated prior to final machining
- Encoder assembly continues

YEAR - 1963

SUMMARY

While the previous year primarily involved getting the program started, the current year saw the star tracker program transform from a paper design effort into a practical reality.

Activity centered around finalizing and releasing mechanical fabrication drawings to the shop for the build process, and accepting delivery of components and subassemblies from vendors.

Preliminary test programs were devised for subassembly and assembly tests and test fixtures in support of the program were designed and subsequently fabricated.

A telescope assembly was delivered by ITT for final assembly and calibration. Subsequent system testing on this unit uncovered deficiencies which led to a number of technical conferences between NASA, Bendix and ITT. Investigations were initiated into the cause of these problems and appropriate design changes occurred.

Encoders were delivered from Baldwin and subsequent problems occurred with lamp power supply variations. Investigation started.

Evaluation testing occurred on torquers, tachometers, resolvers, optics, sun shade designs and paint samples. Deficiencies noted were discussed with the appropriate vendor (if delivered from outside) or engineering group (in house). Subsequent design improvement efforts were started where necessary.

The prototype star tracker was assembled and submitted to a vibration survey, while the major highlight of the year was the operation and demonstration to NASA of the prototype unit as a functioning system (OMA, STE) with the Bendix built DLU. Subsequent testing of this unit brought about a considerable structural and electronic redesign effort, whereby efforts were made to improve the rigidity of mechanical features, extend gimbal movement to $\pm 60^{\circ}$, reduce overall weight and clear up oscillatory problems in STE.

YEAR - 1963

HIGHLIGHTS

JANUARY - JUNE (1963)

ELECTRONICS

- Final telescope checkout - returned to Bendix for final assembly and calibration
- Bendix - ITT conference on manufacture of qual model electronics
- Telescope failure _ HVPS
- Bendix - ITT conference on telescope changes

- Encoder assemblies completed and returned to Bendix for final assembly
- Encoder problems - sensitivity to lamp supply variations

- STE circuits continued; breadboard design completed
- DLU breadboard completed

MECHANICAL

- Star Tracker frames fabricated, heat treated; ready for final assembly
- Rough machining of telescope casting

- Motors, tachometers received and checked out
- Bearings received from vendor
- Optics received - improper design - returned to vendor
- Metal prototype sun shield fabricated
- Sun shield evaluation tests lead to redesign
- Sun shield fabrication methods changed; integral baffles of fiberglass.

- Prototype tracker prepared for vibration survey
- Vibration fixture completed
- Prototype tracker subjected to low level vibration to confirm design

- Design assurance program started for Qual Testing; test data generated for extreme environmental conditions of vibration and thermal vacuum
- Considerable structural redesign and weight reduction effort instituted ($\pm 60^{\circ}$ gimbal movement, new sun shield, lens baffles, addition of ribbing for rigidity).

SYSTEM

- Prototype OMA, STE, DLU operated as system and demonstrated to NASA and tested in command - track modes
- OG instability condition, slewing rates low; gains and compensation changes necessary

- Thermal analysis continues on telescope housing and spherical shell
- Week-long thermal vacuum tests on prototype
- Prototype thermal balance tests performed - no large temperature gradients

JULY - DECEMBER (1963)

ELECTRONICS

- Telescope tests performed at Bendix; null shifts with warm-up - 20 minutes to stabilize, large null shifts over temperature ($-65^{\circ}F$ to $+75^{\circ}F$ = 5 arc min shift), cross coupling problems

- Modules for Qual STE 20% complete

MECHANICAL

- Major effort directed toward final machining, applying finishes to subassemblies in preparation of Qual Star Tracker assembly
- Final machining drawings for gimbals completed
- Drawings for sun shade, thermal shield started
- Spherical gimbal fabrication combines spinning and hydroforming process
- Test samples for selected paint coatings submitted for testing

SYSTEM

- Photomultiplier tube and telescope electronic problems occurred
- DLU - STE tested together; oscillatory problems and malfunctioning module
- Qual Test Plan completed and submitted to NASA; revisions necessary

YEAR - 1964

SUMMARY

The highlight of the current year was the award by Grumman for six (6) production star trackers identical to the NASA Qualification star tracker. The final task statement was negotiated and work immediately began. This work was performed concurrent with the NASA development program.

In the NASA program, further telescope tests were performed on the redesigned electronics and other problems were uncovered. Time was spent in an attempt to pinpoint the cause of these problems. Redesign and/or modification occurred with the encoders and tachometers after extensive testing efforts.

Preliminary assembly of the qual telescope started, however, results from the worst case analyses being performed were then taking final form and it appeared that certain areas of redesign would affect the Qual assembly.

YEAR - 1964

HIGHLIGHTS

JANUARY - DECEMBER (1964)

- Grumman award to Bendix for six (6) production star trackers identical to the NASA Qual star tracker
- Final task statement negotiated with Grumman

ELECTRONICS

- Telescope tests show excessive null drift due to demodulator
- Encoder power supply modified to correct drift over temperature
- Tachometer problem with "Vac Cote" treatment
- New tachometers ordered; AgC brushes, Paliney 7 brushes on Au-plated commutators

MECHANICAL

- Torquer (Inland) problems after vibration; tests repeated - conclusion: Inland torquer rugged unit
- Torquer worked properly after careful reassembly
- Prototype OMA repainted and fitted with fiberglass shroud and covers; unit prepared for thermal balance test
- Test room facilities in preparation, test stand concrete poured, rooms painted

SYSTEM

- Prototype OMA electrically tested, submitted to vibration, resulted in 20 arc second zenith shift, no mechanical discrepancies

- Qual telescope assembly started
- Various WCA's performed upsetting aspect of Qual STE design

YEAR - 1965

SUMMARY

The effort of work throughout the entire year was expended on the NASA qualification effort simultaneous with the Grummán production effort.

A major highlight of the year saw the start of the development effort for the Bendix-designed telescope electronics. This situation was brought about because of continuing technical problems with the ITT-designed system. The ITT demodulator and video amplifier modules were redesigned and various tests supported this design effort. The STE assembly design was completed, however, results from the worst case analyses led to redesign efforts for the star tracking detector and track command switch.

Results from thermal analyses brought about a change in the encoder temperature range to a lower Qual temperature of -70°F. Extensive testing was performed to vary the design at these temperatures.

The first Pre Qual star tracker was completed using the latest configuration and circuitry design improvements specified at that time. The unit was functionally tested and shipped to General Electric for solar impingement evaluation tests.

At this point in the program, Bendix observed the first occurrence of what eventually became known as HV arcing. This phenomenon occurred in preparation for conducting the solar impingement tests.

A thermal balance test was performed to better understand the star tracker distribution temperatures.

Work at this point was rapidly progressing toward the build of the Qual unit and because of this effort, the in-house development of the Bendix-designed telescope electronics was permanently stopped.

YEAR - 1965

HIGHLIGHTS

ELECTRONICS

- WCA performed on ITT telescope circuitry shows possible problem areas: excessive null shift vs. star magnitude, power supply variations.
- ITT redesign effort on video amplifier and demodulator; tests support design

- STE - design of all modules and overall assembly completed
- WCA leads to redesign of star tracking detector and track command switch

- Encoder temperature range changed; acceptance = $-50^{\circ}F$, qual = $-70^{\circ}F$
- Seven (7) encoders tested to $-70^{\circ}F$; six (6) successful, one (1) fails
- Encoder power supply redesigned to use unregulated 28 VDC
- New encoder lamp spec to vendors
- Lamp life tests completed

MECHANICAL

- OMA final assembly drawings completed
- Shroud configuration finalized
- Qual telescope delays due to technical problems

- Squib: fabricated and test fired developmental model of gimbal decaging actuator

- Tachometer life tests begin
- Sunshade redesign investigation; steel baffles replace former molded baffles

<u>SYSTEM</u>

- In-house development effort for telescope electronics started because of ITT technical problems
- In-house effort stopped because of major STE design changes

- First Pre Qual star tracker completed
- PQ unit functionally tested successfully
- PQ unit shipped to GE solar impingement facility for extensive sun shade tesing; sun shade problems at high sun angles; sun shade redesign effort
- HVPS arcing occurred during solar impingement
- Thermal Balance test performed

- NASA directive for calibration of telescopes against new star standard

- Parameter variation study and stress analyses started
- Radiation tests started at Grumman
- RFI tests started

YEAR - 1966

SUMMARY

The major highlight of the year was the official start of the Qualification Test Program on November 7, 1966.

Work on the Grumman production star trackers continued along with the engineering development and qualification build taking place for the NASA program. However, a hold was placed on the production program by Grumman when a HV arcing problem was discovered. A separate task statement was authorized by NASA to find a solution to this problem and a thorough investigation program was started. This program was to ultimately last more than one year, ending during 1967. Most of the work was accomplished during the 1966 period.

The design for the qual unit was primarily frozen during the year as results from the various investigations began to show marked improvement. The various design efforts involving components and subassemblies were proving the existence of a sound design. A marked effort was made to incorporate these results into the qual unit as quickly as possible. The Qual OMA and STE were assembled, functionally checked and certified for the Qual Test Program.

YEAR - 1966

HIGHLIGHTS

ELECTRONICS

- Pre Qual STE package completed, identical with Qual STE; Qual fabrication in process
- Encoder life test continues; 1500 hour run between temperature range of +100°F and -70°F; 16th track erratic; encoder cleaned and irregularity clears up
- Encoder power supply redesign effort for RFI levels
- Encoder lamp study; goal is long life with constant illumination
- Baldwin encoder lamp procurement specification released
- Tachometer test completed; 2000 hours with no degradation
- ITT telescopes SN-5,6,7 unusable because of poor quality workmanship; Bendix Quality representatives stationed at ITT
- STE variations between Qual and Production units unacceptable to Grumman; new STE package built incorporating new procedures; Grumman resident engineer follows NASA program
- RFI testing on Pre Qual unit leads to design changes

MECHANICAL

- Sun shade manufacturing techniques investigated; embedded stainless steel baffles vs. glue process
- Baffles and aperture stop added near photomultiplier tube

- Optical coating investigation: Parson's Black, Luxorb, Floquil
- Successful solar impingement test with PQ unit and new sun shade
- Sun shade and sensors ready for qual unit
- OMA final balanced; certified for Qual Test Program
- Fabrication techniques developed for optical grade plastics membrane to protect sun shade, recommendations made

SYSTEM

- HV arcing occurs during investigation tests using telescope SN-5
- Investigation starts for prevention of HV arcing; proposal and presentation to NASA August 23; work centers around photomultiplier, HV power supply, HV wire, potting material; test procedures generated
- Hold is placed on production trackers by Grumman
- Thermal vacuum chamber installed and checked out
- Radiation tests at Grumman concluded with successful operation
- Qual Test Plan delivered to NASA (Revision B); Revision C follows
- Qual OMA and STE certified for test
- Qual test begins September 7, 1966
- Test equipment problem and $\pm$28V reversal causes star tracker breakdown; investigation starts

- STE failure analysis: 17 modules unaffected
10 stressed
1 failed
- OMA failure analysis: 2 modules failed
- Action taken: Test equipment modification and detailed test procedures; all stressed and failed modules replaced; system checked and certified
- Qual Test Program begins November 7
- Test phases completed: Full functional, acceleration, shock, vibration, thermal vacuum and preparation for solar impingement

YEAR - 1967

SUMMARY

This particular year of the program saw major strides taken in the improvement of the Bendix star tracker. The Qualification Test Program, which started in November of 1966, was completed in February, 1967. While many of the program objectives were met, some problems and out-of-spec conditions did occur.

The wealth of test data generated over the four month test program was carefully analyzed over the following months in an intensive and detailed engineering investigation. All aspects of engineering disciplines were involved in the investigation. These included mechanical, electrical, servo and optical engineers, mathematicians, physicists and heat transfer specialists; all involved in attacking problems such as encoder flicker, zenith shifts due to shock, vibration and thermal vacuum, tracker oscillations under different conditions, false star presence signals, RFI and voltage transient problems, star magnitude threshold variations and optical paint flaking.

The Qualification star tracker (designated with telescope serial number SN-8) was carefully disassembled in the major analysis that occurred. Test programs tailored to a specific problem were instituted and solutions to these problems were uncovered as the year progressed.

Bendix, midway through the year, incorporated the solutions into the Pre Qual 2 star tracker and conducted an unofficial Qual Test Program. The resulting data supported the directions of the investigation and preparations were made to assemble a star tracker into an updated qualification configuration.

Concurrent with the above activity, Bendix successfully completed the investigation into the high voltage arcing and corona discharge phenomena. Presentation of results were made to NASA and Grumman and permission was granted to incorporate the Bendix "HV Fix" into the telescope design. Upon this concurrence in design, Grumman released the "Hold" on the production units. All trackers were disassembled in preparation of incorporating the hi-voltage solution.

A delay in the program was then encountered when cracked photomultiplier tubes (after depotting tube base) were discovered (SN-8 Qual unit and a production unit). An investigation was started immediately into the cause of this problem.

The results of this work were incorporated in a presentation and report made to both NASA and Grumman in October, 1967. In summary, Bendix recommended a continuation of the OAO star tracker program using Bendix-designed telescope electronics with new hi-rel photomultiplier tubes and substitution of telescope SN-13 for SN-8 as the new Qual star tracker. Eventually these recommendations were accepted.

The end of the year saw the "HV Fix" incorporated into telescope SN-13, the new Qualification unit.

YEAR - 1967

HIGHLIGHTS

- Qual test continues with solar impingement, modified RFI and final functional; test program ends in February

- Investigation of Qual test out-of-spec conditions and failures begins

ELECTRONICS

- Encoder flicker problem (loss of 16th track) investigated; lamp interference, epoxy buildup causing defocusing
- Power switch redesign effort starts; separate HV turn on
- False star presence problem investigated; star presence delay circuit design effort with eventual use
- Star, magnitude threshold variation problem investigated
- Common grounding instituted
- RFI filter redesign
- Servo interrupt circuit design effort with eventual use

MECHANICAL

- OMA diagnostically disassembled with investigation
- Zenith shift investigation starts; shock, vibration and thermal vacuum, prism mounting, tracker torque level in TV changed
- Bearing housing material investigation starts; new material found, incorporated into new design

- Torque material investigation starts; new torquers: Ag-MoS_2 brushes, gold-plated commutators

- Squib fuse relocation
- Interchangeability of long and short sensors required; ITT long sun sensor and trigger replaced by Bendix design; earth angle requirement changed to 10.5° $\pm 1.5^{\circ}$
- Qual telescope (SN-8) prepared for HV Fix
- SN-8 photomultiplier tube base cracked; investigation starts; results and recommendation made to NASA
- STE mounting changes made to conform to Grumman directive
- Optical coatings adhesion investigation starts (Luxorb-prims, Parson's Black-sun shade); new preparation and application procedures successfully generated

SYSTEM

- Hold on production units released in April
- HV acring investigation program successfully completed; test procedures and specifications generated; HV fix ready for Qual unit
- Servo oscillation problem investigated; grounding changes, DLU noise immunity raised, new test procedures instituted
- Pre Qual 2 star tracker prepared for unofficial Qual test program; PQ system updated with resulting Qual investigation solutions; test program starts

- Design Review held in October; discussions held on Qual status, investigations, PQ 2 test results and program alternatives. Bendix report (TR4051) documents review
- Telescope SN-13 substituted for SN-8 as new Qual unit because of cracked tube problem
- HV fix incorporated into telescope SN-13
- Changes made to OMA and STE hardware in preparation for new Qual assembly
- Detailed thermal analysis starts in November

YEAR - 1968

SUMMARY

The major highlights of the year saw the go-ahead award from Grumman in April to build and test production units using Bendix-designed telescope electronics. Work progressed to the point where a telescope was assembled in module form and tested successfully over temperature. In September of 1968, Bendix received a "Stop Work" order from Grumman and the contract was eventually "terminated at the convenience of the government". The NASA Qualification Program, however, continued.

Technical problems occurred during the assembly and test of the Qual unit and repeatedly extended the program. However, by year's end the star tracker was ready for the start of the Qualification Test Program. At this point an encoder malfunctioned and had to be replaced and the Qual Test Program could not start until January, 1969.

The major accomplishment for the year included the following:

a. Successful qualification of the SN-13 photomultiplier tube and HVPS subassembly over thermal vacuum-partial pressure

b. Successful qualification of the SN-13 telescope assembly over thermal vacuum-partial pressure.

c. Successful qualification of the long earth sensor over thermal vacuum

d. Successful qualification of the long sun sensor over thermal vacuum

e. Complete assembly of Qualification Star Tracker (SN-13) with in-process assembly tests throughout (torquers, tachometer, encoders, resolver).

YEAR - 1968

HIGHLIGHTS

ELECTRONICS

- Circuitry work generated by Qual test investigations completed and incorporated into design framework
- Threshold variation investigation concluded with results for improved controls and procedures for star magnitude calibrations and testing in general
- Ready for new Qual Test Program

MECHANICAL

- Short sun shade and short earth and sun sensor requirements eliminated
- Qual Test investigation solutions incorporated into Qual hardware
- Ready for new Qual Test Program

SYSTEM

- Bendix receives go-ahead for production units using Bendix-designed telescope electronics
- Bendix designed electronics to use hi-rel parts; new hi-rel photomultiplier tube spec written (outgrowth of cracked tube problem)
- PQ 2 test program continues and is eventually completed with results indicating solution to most Qual Test failures
- SN-13 (new Qual) tube and HVPS prepared with HV fix; humidity problem occurs with potting compound - difficulty in curing; tube-HVPS tested in thermal

vacuum with eventual problems; problems related to poor workmanship

- SN-13 tube - HVPS successfully passes thermal vacuum - partial pressure Qual test

- SN-13 telescope assembled; TV-partial pressure tests start; ITT module (demodulator)fails; Bendix replaces failed module with new demodulator and video amplifier combination; tests restart and eventually end successfully
- Glow discharge problem occurred with tube during tests; investigation made; NASA waives requirement

- Qual OMA and STE assembly in progress
- Qual Test Plan and Procedures submitted with approval given at subsequent revision level
- Qual Sensor Test Plan and Procedure submitted with approval given at subsequent revision level

- Qual test for earth and sun sensors performed successfully

- Bendix receives "Stop Work" order from Grumman on September 12, 1968 on Bendix electronics development effort and production program

- NASA Qual Program continues

- Qual OMA and STE assembly completed in October; OMA subjected to low level vibration for stability purposes; preliminary functional check performed

- Electrical check of OMA shows encoder problem, investigation shows low photocell output for inner gimbal encoder
- Qual inner encoder replaced with subsequent partial disassembly of OMA; tracker reassembled

YEAR - 1969

SUMMARY

The Qualification Test Program began January 16, 1969 and ended June 4, 1969.

The test program was considered a success with most problems or spec deviations generated by the original Qual Test of 1966-67 being solved. The major highlight of the program was the within-spec accuracy result (less than 22 arc sec per axis; 30 arc sec total) of the star tracker over all environmental conditions of acceleration, shock, vibration and thermal vacuum. At no time during the test program were there encoder problems or malfunctions, out-of-spec zenith shifts over thermal vacuum variations, star tracker oscillations (command or track mode), voltage transient problems, false star presence signals, star magnitude threshold problems or flaking of optical paints. Zenith shifts after shock and vibration occurred, however, discussions with NASA personnel indicated a capability to recalibrate a star tracker system in space and no concern was voiced about the matter. Toward the end of the Qualification Test Program and during routine preparatory tests prior to performing RFI, the Qual tracker star presence signal was permanently lost. Subsequent investigation indicated a failed ITT demodulator module within the telescope assembly. Under these conditions it was not possible to commence RFI. Discussions with NASA representatives led to the granting of permission to substitute the Pre Qual 2 OMA for the Qual OMA. This was possible because of the near identicality of the units.

Since this substitution allowed the continuation of the test program through the performance of RFI, meaningful data was attained. The remainder of the test program was performed using the Pre Qual 2 OMA and Qual STE.

A complete and detailed Qualification Test Report (No. 7151-SS-69-1), documenting the entire test program and independent of this final report has been written and delivered to NASA.

YEAR - 1969

HIGHLIGHTS

JANUARY

- Assembly of Qual OMA and STE completed
- OMA and STE functionally checked for proper electrical operation
- Qual Test Program begins officially January 16, 1969
- Full Functional, Acceleration and Post Acceleration accomplished

FEBRUARY

- Shock, Post Shock, Random and Sine Vibration, Post Vibration accomplished

MARCH

- Thermal Vacuum,Post Thermal Vacuum and Solar Impingement (at General Electric facility) accomplished

APRIL

- Post Solar Impingement accomplished
- Sudden permanent loss of star presence signal from Qual OMA occurs; investigation shows defective ITT demodulator module within telescope electronics
- Permission received to substitute Pre Qual 2 OMA for Qual OMA and continue Qual Test Program

MAY - JUNE

- Qual Test Program continues using Pre Qual 2 OMA and Qual STE
- RFI and Final Full Function accomplished

- Bendix-NASA Qualification Test Program completed
  June 4, 1969

3.2 Part B - Major Contributions

3.2.1 Sun Shade

In order for the OAO Star Tracker to operate at angles relatively close to the sun. It was necessary to design a sun shield to effectively reduce the sun's intensity relative to a star. The difficulty of this task is emphasized by the fact that the sun's intensity is approximately 3.5×10^{11} times brighter than a +2 magnitude star.

The development of a sun shade was begun in late 1962. A basic design was conceived as early as February, 1963.

By August, 1963, the design was further developed and an engineering drawing had been completed.

By early 1964, a fiberglass model of the shade had been fabricated and arrangements were made to test the shade.

Testing a sun shade requires not only solar simulation, but also a large vacuum chamber. The chamber must be large, painted black, and still fully baffled in order to provide adequate absorption of the scattered sunlight. Vacuum is necessary not only to settle all dust particles, but also to eliminate light refraction due to molecules in the air.

The first full-fledge vacuum test was conducted in May, 1964. Unfortunately, this test was termed a complete success. Two subtleties which were not recognized at this time were (1) the star threshold sensitivity of the star tracker system was set for a very bright star and (2) a stop used to simulate the field-of-view had the effect of setting back most of the baffles in the cylindrical portion of the shade.

Between this test and the next series of tests conducted in October, 1965, the shade was redesigned to accommodate some spacecraft interferences. The original design was expected to have a margin of efficiency adequate to allow the deteriorating effects of the modification. However, the tests revealed offset errors due to the sun of up to 7 arc minutes even at high sun-optical axis angles.

In December 1965, this same shade was retested in order to obtain the additional data necessary to complete the redesign of the shade which had begun after the October failure. The data from these tests in addition to the basic concept of the shade, were extensively analyzed by The Bendix Corporation. The results of this investigation showed the size of the baffle edge to be extremely important.

Subsequently, a shade was constructed using thin metal baffles embedded in fiberglass. The inside of the thin baffle was ground to a razor edge to further reduce reflections from the edge. The development of the construction techniques in themselves were extensive.

Various versions of this metal-fiberglass shade were tested in January and March, 1966, resulting in an evaluation of a successful shade.

The sun shade's effectiveness was further confirmed during qualification testing conducted during January of 1967, and again through the successful solar impingement test at General Electric during March, 1969.

3.2.2 High Voltage Investigation

Background of HV Problem

One of the problems encountered on the first OAO vehicle was its suspected high voltage malfunction. Similar problems have been noted on seven other satellites - (OGO, OSO-I, OSO-II, S-51, S-52, S-6 and Nimbus) during thermal vacuum testing or in orbit. Aside from the indirect causes of the high voltage (HV) problems, they were all a direct result of the presence of a gaseous dielectric in a high voltage field.

High voltage systems can be of two distinct types: (1) those employing the ambient gas as a dielectric or (2) those employing solids and/or sealed gases or liquids as dielectrics. Systems using the ambient gas cannot be operated in a particular pressure region without glow discharge while the second type may be safely operated at any reduced pressure.

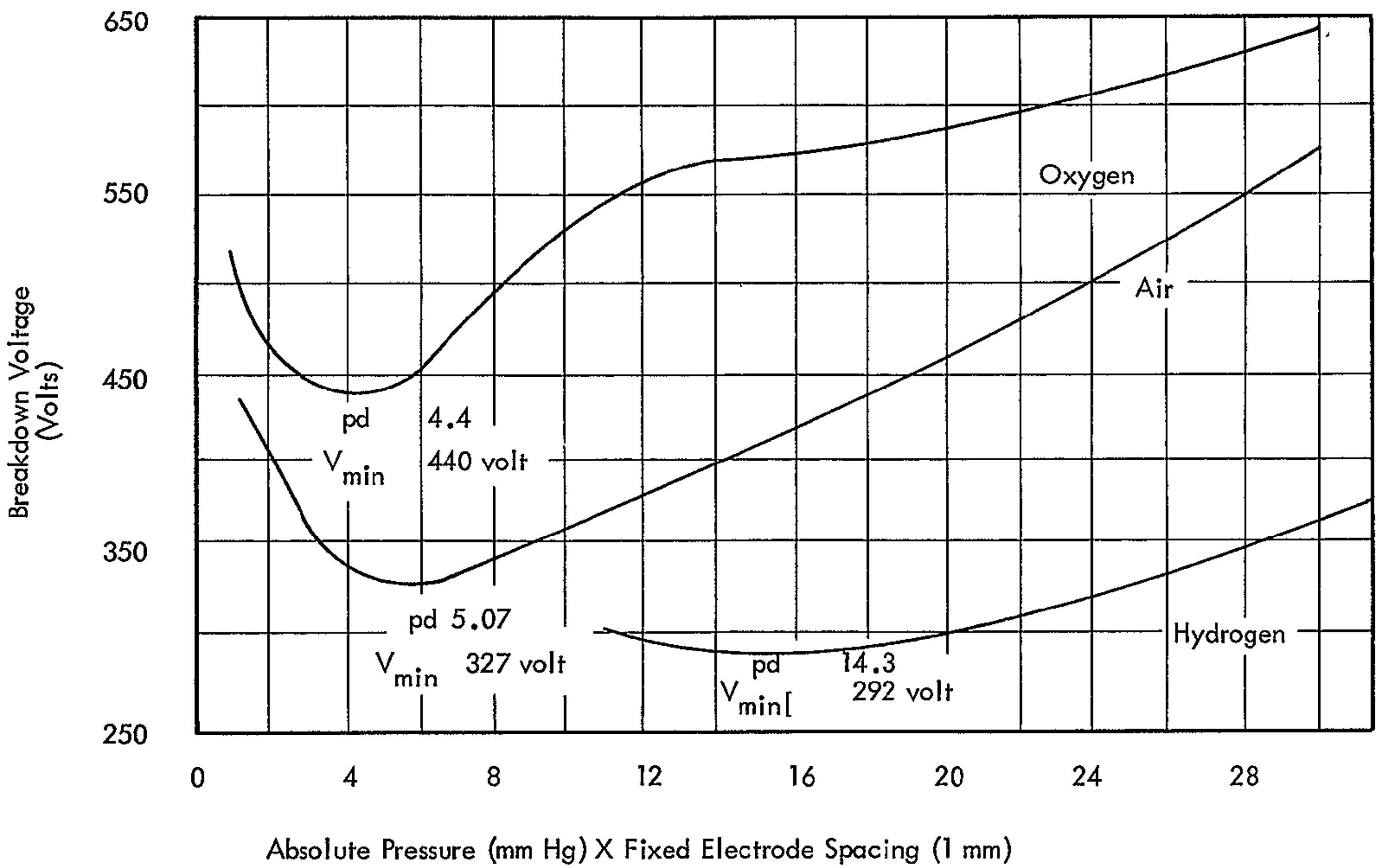
Initially all star tracker HV systems on the OAO used the ambient gas as a dielectric. After the OAO problems arose, NASA-Goddard decided to modify the star trackers to operate at any reduced pressure. Bendix was awarded a contract to investigate, design, and develop such a HV system. This program has been highly successful and has yielded a design, which will be implemented on all flight star trackers.

High Voltage Breakdown Theory

High voltage arcing problems are a result of excessive leakage or dielectric breakdown. The most outstanding difference between liquid or solid dielectrics and gasses is that the dielectric strength of gases are a marked function of pressure. This function has been studied in great detail for most gases and bears the title of Paschen's Law; Paschen's Law is plotted in Figure 3-2 for oxygen, air and hydrogen.

From these curves, it is seen that the dielectric strength decreases, reaches a minimum and then increases, with decreasing pressure and constant gap size. It is significant to note that the dielectric strength is a function of the pressure-distance product and not of pressure alone. This effect can be explained by considering a pair of electrodes, of fixed spacing immersed in a gas. If a potential is applied between the electrodes, the free electrons will be attracted to the anode and the ions toward the cathode. The kinetic energy achieved by these particles is a function of the applied field and the mean free parth (mfp) of the gas.

On the "average", these particles will travel a distance equal to mfp at which time they will collide with another gas molecule. The collision may be elastic and result in recombination, or may dislodge additional electrons. The nature of the collision is a function of the energy the particles achieve before impact. If the rate of generation of particles is equal to the rate of combination, the gas will appear to be an insulator. If the current carriers are generated more rapidly than they are absorbed, the gas will "breakdown" and rapidly become a good conductor. At high partial pressures the mfp is short and a large electrode potential is required to cause a breakdown. Because the mfp is inversely proportional to the pressure, the breakdown potential will occur at lower values as the pressure is reduced.



Paschen's Law Curves for Oxygen, Air, and Hydrogen
with Electrode Spacing Fixed at 1 mm
FIGURE 3-2

This situation will prevail until the mfp becomes long enough, such that the probability of secondary collisions is small. When this happens, the required electric field will reach a minimum and must then be increased to cause ionization.

There are several parameters which affect the design of a high voltage system. One of the key parameters is the permittivity of the materials in which the potential field exists. The nature of the potential distribution across the dielectric is such that the major gradient is always across the air. This places additional stress on the already weakest insulator.

In the discussion of Paschen's Law it was noted that ionization of the gaseous media resulted when the kinetic energies of the charged particles were sufficiently high. In the case described, the mechanism which did this was electric field acceleration. It should be noted that these energetic particles, radiation (light, X-rays, Gamma-rays, etc.) and electric field or thermal emission of particles from materials on the boundary of the gas. Temperature also affects gases as it is related to the "mean free path". In contrast, solids have relatively stable dielectric properties when exposed to various temperatures, pressures, and energetic particles.

Bendix HV Solution

Leaning heavily on theoretical concepts as described above, Bendix has designed, analyzed, and tested a high voltage system suitable for operation at all partial pressures. For this development, the HV system was separated into four distinct parts (1) the HV power supply (2) the HV wire (3) the "phototube" and (4) the HV terminations. The design is predicated on surrounding all HV electrodes with a stable dielectric and using electrostatic shielding to terminate the potential field in this media.

The HV power supply is placed in a hermetically sealed can with glass hermetic electrical feed-throughs. The HV terminal is isolated from its surroundings by electrostatic shielding. This shielding assures termination of the potential field within the solid dielectric within the shield. The can is filled with 1.2 atmospheres of a 90/10 nitrogen-helium gas, which provides a stable dielectric and a means of leak detection. The maximum leakage rate to satisfy the design requirements was analytically determined (MT-13,142) and is specified for the mechanical configuration. Six HV power supplies were fabricated and successfully subjected to several hundred hours of testing over the maximum thermal-vacuum qualification exposure. The test plan is described in MT-13,124 with the results and summary presented in TR-4008.

The high voltage wire is identical to the type that has been "space proven" on the Nimbus satellite. The wire is a special type of high voltage coaxial lead. The dielectric between the inner and outer conductors is filled with a silicon rubber, within which the potential field terminated. The wire was tested at reduced pressures for 26 days. The tests are described in MT-13,126 and the results are discussed in TR-4012.

The photomultiplier tube is potted in a cylindrical metal, magnetic shield. The front end of the shield is closed with a disc of magnetic material. The shielded HV wire terminates in the divider network located on the back end of the tube. The electrical components in this divider network are hard wired to the tube header. A special procedure (TR-4001) has been developed to apply potting material into this region with excellent adhesion. The divider network and tube are electrostatically shielded by the magnetic shield and an electrostatic shield placed in the potting material above the divider network.

All of the above items have been thoroughly tested in thermal-vacuum for several hundred hours. Proper operation has been demonstrated for all pressures and temperatures between $-68^{\circ}F$ and $130^{\circ}F$. Extensive testing has been performed on the potting material and its adhesion over the qualification thermal range (See TR-4005). Six potted tubes were connected with HV supplies with the coaxial wire and exposed to 385 hours of thermal vacuum exposure. The procedures followed and the test results are described in TR-4011. The tubes were tested electro-optically before and after the exposures to detect any damage (See MT-13,125). The completed HV system was qualified at reduced pressures in thermal-vacuum. The general procedure followed is given in TR-4028.

3.2.3 Telescope

The telescope is the input sensor in the star tracker servo system. Its function is to generate cartesian coordinate error voltages proportional to the angular displacement of a guide star off boresight. In the OAO system, the error voltages are the inputs to a Type 1 servo system and as such are reduced to zero when tracking. Thus, the stability of "null" as a function of environment and life is very important. The practical realization of "null" stability was achieved in the OAO only after exhaustive testing and development. Investigations led to improvements in both the electrical and mechanical aspects associated with a null-stable tracker. Before these developments, null shifts as great as 2 arc minutes were experienced. Through a process of elimination the causes of the errors were traced to the following items in the telescope.

1. Changes in the error signal with changes in star illumination.

2. Movement of the prism and lens in the telescope housing over temperature variations.

Error signal changes with different star illumination levels were rectified through the development of a process called "dynode shading". This procedure insures a uniform secondary electron gain as the star image is scanned across the aperture of the tube. This method eliminated 60 seconds from the null shift.

It was found that a tilting of the lens and hence a relocation of the star image was produced by contraction of the lens retaining ring over the cold temperature environment. The condition was rectified by the proper selection of the retaining ring torque at room temperature.

The remaining shift was traced to movement of the prism within the telescope housing. The magnitude of the shift was verified by actually measuring the movement of the prism with respect to the telescope housing. The test was performed by removing the lens from the telescope casting to permit an autocollimator to view the entrance aperture of the prism. The aperture was coated by a vacuum deposited aluminum mirror surface specifically for this measurement. Autocollimation data was compared from this surface and from a mirror mounted in the telescope housing as the entire unit was cycled over temperatures ranging from $+55^{\circ}C$ to $-55^{\circ}C$. The results of this test conclusively proved that the major cause of the telescope shift over thermal environments was the movement of the prism.

This discovery led to a change in the design philosophy of the prism mounting configuration. Whereas in the past the prism rested on the floor of the wobble plate it is now supported by a three pad suspension system and secured by straps.

The system functions from a low electrical current level produced by the star signal (from 0.2 to 20 microamperes). Nevertheless, the system provides the same response whether the guide star is a -2 or a +3 star magnitude, a ratio of intensity of 100 to 1. The system thus remains linear for all star magnitudes and shot noise inherent in the signal.

This is accomplished through the use of an amplifier with an automatic gain control and selective filtering. The presence of shot noise further required the addition of hysteresis to eliminate ambiguous operation of the star presence signal and star magnitude detectors.

3.2.4 Deflectable Photomultiplier

Photomultiplier Development

A quantitative determination of the characteristics of individual photomultipliers is a prerequisite for the selection of those suitable for use in a star tracking application. Phototube evaluation requires the development of laboratory procedures that will allow the measurement of tube parameters.

Those of particular importance are the following:

1. Anode Luminous Sensitivity to a source of known spectral distribution (Amps/Lumen)
2. Peak Anode Radiant Sensitivity (Amps/Watt)
3. Anode Dark Current (Amps)
4. Current Amplification (Gain)
5. Cathode Spectral Response

Procedures have been developed to measure each of the above characteristics and are detailed in the following reports: MT-13,125,"Test Plan for Measuring Photomultiplier Characteristics Before and After Environmental Exposure:"; TR-4040, "Procedure for Measuring Gains and Spectral Response of Photosensor."

It is also desirable to monitor tube sensitivity throughout the construction of a star tracker system. Procedures have been developed to perform this task as documented in TR-4030 "Test Plan for Measurement of Photomultiplier Sensitivity for the High Voltage Program," and TR-4031 "An Investigation Procedure for Photosensors".

Bendix has also developed a procedure to evaluate a phototube-deflection coil combination in the laboratory. The test that is run using this setup allows one to determine the feasibility of using coil or tube in a particular star tracking application. Hence, the characteristics of the detecting elements of a tracker can be measured before they are actually incorporated into an entire system.

This testing has been done and is documented in TR-4077, "Electron Beam Deflection Linearity with Respect to Coil Current".

Wave Shape Forming (Dynode Shading)

It has been found that an apparent change of star location with change in star illumination can be caused by operating the image dissector photomultiplier of a cruciform star tracker with nominal voltage divider values. This problem has been eliminated by tailoring the potentials of the multiplier stages of the phototube.

The apparent star shift is caused by the fact that the gain of each stage of the multiplier is a function of the angle and velocity of the impinging electrons. Hence, as electrons are scanned across the dynodes, a different multiplier gain can be experienced within the scanning cycle. This change in the absolute output of the tube can affect the star position information contained within the wave form. This phenomenon is especially critical when dim stars are being tracked.

Bendix has eliminated the problem by employing a waveform shaping device that allows one to judiciously select the dynode potentials of the multiplier. The star position obtained within the waveform of a "dynode shaded" tube is independent of the intensity of the star being tracked.

This subject has been detailed in two Bendix reports, MT-13,128 Issue A, "Wave Shape Forming of Deflectable Photomultiplier Used in Star Tracker," and TR-4063, "Null Stability as a Function of Shot Noise in a Cruciform Modulated Star Sensor".

3.2.5 Star Calibration

Bendix has developed and applied a star calibration technique through a standard of known absolute spectral content. This technique (MT-13056, A New Photometric Transfer Technique For Star Simulator Calibrations through the NASA OAO Star Simulator) was successfully used for OAO and is being applied to the ATM star tracker program. Bendix participated in a "round robin" calibration procedure designed to assure star calibration agreement for all star trackers used on OAO. In addition, Bendix was required to set star magnitude recognition threshold levels for its star trackers and transfer star magnitudes from a standard star simulator to a collimated star simulator used for star tracker testing.

Star Magnitude Systems

All star magnitude systems are based on the relationship of the energy intercepted by a detector from a particular star to the energy intercepted by the detector from a standard star (or stars). The standard stars normally selected are of the AO type (blue). The detector may be the human eye (producing "visual" magnitude), a photometer or an image dissector used in a star tracker.

Since the spectral response of different detectors vary, the energy "seen" by different detectors will also vary. Furthermore, since star magnitude systems are dependent upon the star energy reacted to by a given detector, a unique star-magnitude system will be generated for a given spectral response.

Absolute Calibration

The method of absolute calibration requires the spectral determination of a standard star and a point source transfer standard star simulator. Absolute spectral data for an AO-V type star is available and has been used by Bendix for OAO calibrations. The initial calibration procedure mathematically specifies a star magnitude for the point source star simulator standard based on the spectral response of the sensor, the spectral content of the simulator and the spectral content of an AO V star. The sensor then views the point source standard and the resulting output current is defined as representing the star magnitude previously calculated. Other star magnitudes are related to other sensor currents by a star magnitude equation. In order to predict the tracker operation to stars other than the AO type, the relative spectral content of the star must first be established.

In the case of various stars, data has been obtained by the spectral measurements of various astronomers. Unfortunately, since monochromatic stellar photometry data is not available for all stars, a black body spectral distribution is assumed, corrected for absorption lines and the corresponding "blanketing effect" (the re-emission of absorbed energy at longer wavelengths). The magnitude of these stars is determined by wide band photometry methods such as the UBV system. This magnitude is then analytically adjusted to a particular detector.

3.2.6 Luxorb

An optical coating (Luxorb) is applied to the unused areas of the prism and lens element edge to reduce off-axis light. Unless substantially attenuated, this stray light can, through multiple internal reflections, reach the detector and appear as extraneous noise.

Several problems in applying Luxorb to optical surfaces became manifest through utilization in the OAO Program.

Physical deterioration of the Luxorb coating on OAO telescope prisms occurred in the temperature range, 0 to 6^{o}F in vacuum. The causes of this deterioration were isolated by a series of thermal-vacuum exposures that simulated OAO test conditions. These environmental tests and results are described in detail with corrective action in TR-4089, ("A Technique to Eliminate Deterioration of Luxorb on OAO Star Tracker Prisms")

As a result of these investigations, Bendix has developed a technique to apply a Luxorb coating that will withstand solar radiation and thermal-vacuum exposures at temperatures as low as -50°F. Optical measurements before application insure a matching of Luxorb's refractive index with that of the optics; a condition necessary for a high degree of off-axis light attenuation.

3.2.7 Earth and Sun Sensors

Earth and sun sensors are used on the long shade Bendix Star Tracker to provide protection from direct earth and sun illumination. Each of the sensors was individually designed to meet specific trigger angles and temperature specifications to match their related trigger electronics. It was experimentally determined that multiple element photovoltaic designs offered the most versatility and sensitivity to meet the sensor requirements.

Design of the sun and earth sensor required a detailed analysis of the zero space sun intensity and spectral output as well as the earth's coefficient of reflectivity (albedo). Knowledge of the spectral response of silicon photovoltaic cells was also needed to determine the total amount of energy impinging upon the voltaic cells from the sun and earth. Another analysis was performed that compared the spectral emissivities and responses of the sun, earth, voltaic cells, and tungsten light at various color temperatures so that laboratory models of the sun and earth, illuminated with tungsten light, would be equivalent to the actual sun and earth Analysis is more completely defined in TR-4034, "Determination of Earth Albedo Intensity at .35 Albedo and Relative Intensities of Tungsten Lamp and Sunlight Illumination".

Part of the development work accomplished in the sensor program was spent on the design of a sun simulator and earth simulator so that sensor designs could be adequately tested. The earth simulator required a design that would simulate the earth's radius of curvature, the satellites orbital altitude, and the earth's lambertian scattering of impinging light. Calibration of the earth simulator is outlined in TR-4039, "Calibration of the OAO Earth Albedo Simulator".

The sun simulator was built around a stable high output tungsten halogen source that allowed a narrow beam spread at an energy output equivalent to zero-space sun.

Bendix has developed elaborate test procedures for its sensor program that are performed at several intervals during and after mechanical buildup. These procedures are outlined in TR-4042, "Sequence of Tests Performed on OAO Star Tracker Sun and Earth Sensors".

3.2 8 Gimbal Alignment Technique for OAO System

The star tracker optical mechanical assembly requires precise measurement of the alignment of its gimbal axes, mounting pads, spacecraft alignment pads, and the zenith positioning of its optical axis.

These measurements are critical and are checked optically to a reference surface which represents the rotational axis of the outer gimbal. Thus, it is absolutely required that the optical pick-off reference be accurately aligned to the outer gimbal axis and its accuracy assured throughout each checking and alignment operation.

The optical pick-off assembly is mounted to the outer gimbal axis by means of a two-point expanding adapter which locks solidly to a hollow shaft. The optical cube of the assembly has two reflective faces 90° to each other within 1 arc sec and is adjustable in three planes.

The one reflective face is aligned to the outer gimbal axis within 3 arc sec. The second reflective face is adjusted radially about the outer gimbal axis until it is aligned to the inner gimbal axis mirror to better than 3 arc sec. The optical mirror on the inner gimbal rotational axis is also aligned to 3 arc sec or better to that axis.

Where gimbal rotation is limited, as the gimbal system of the star tracker, accurate alignment of the optical reference to the gimbal axis is very difficult when following normally practiced methods. Bendix has (1) defined a systematic procedure for determining mirror runout where restricted rotation exists and (2) the correct manner of adjustment. This technique is described in (GAS) 1892291 alignment procedure. By use of the axes'optical references, the inner and outer gimbal orthogonality is certified.

The three point mounting pad configuration is checked for 5 arc sec parallelism of the two planes described by the pads to the outer gimbal axis. An optical checking gage with its optical face aligned to the two planes of its mounting surfaces to better than 2 arc sec is mounted and secured to the unit by use of 3 screws. The optical face of the gage and the outer gimbal reference are then compared to determine mounting pads to gimbal axis alignment.

The accurate alignment of the unit's mounting pads to gimbal axis permits repeatibility of system alignment when mounting on various test stands, and spacecraft.

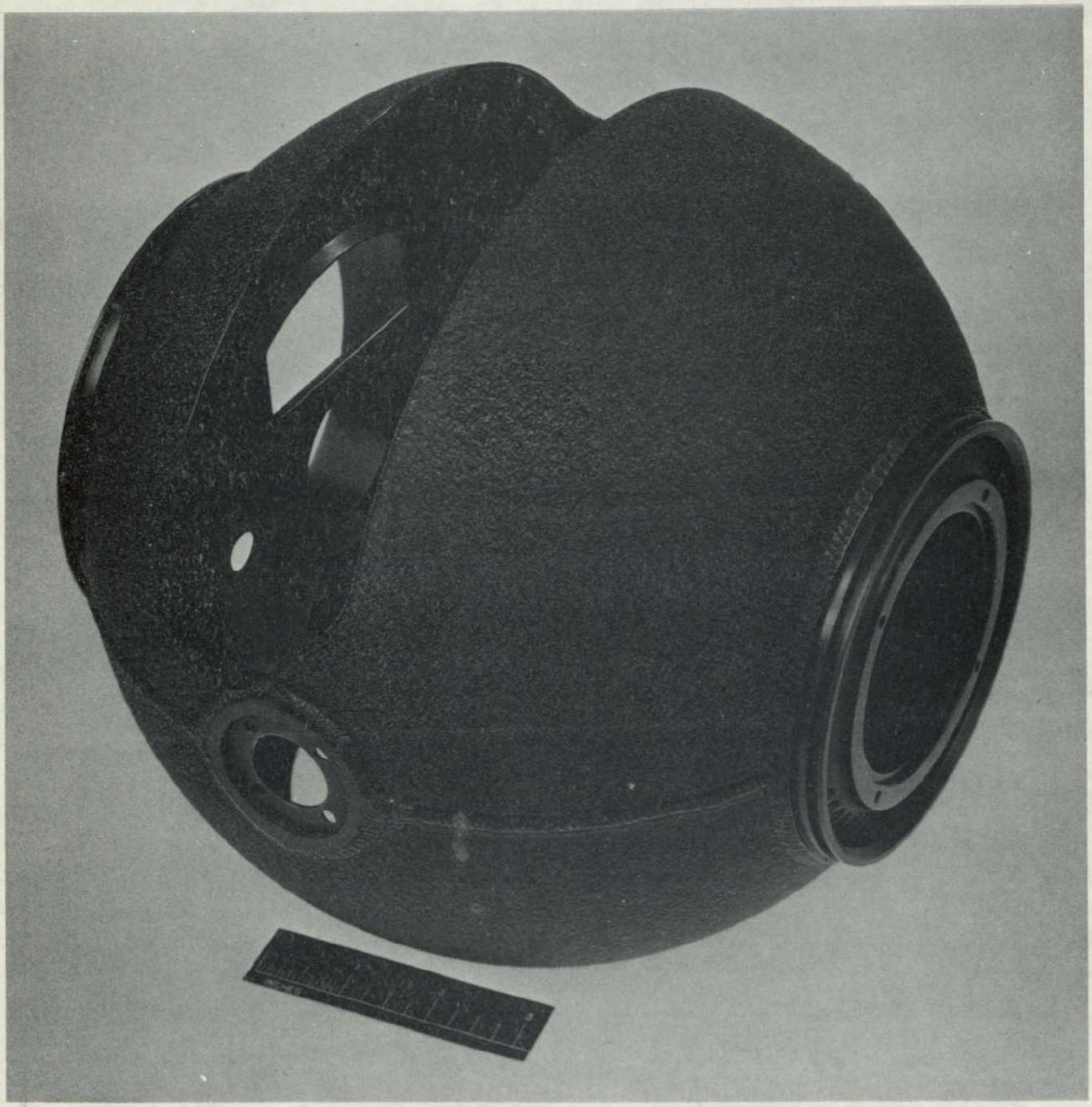
On the OAO system, an arrangement of pads similar to the mounting pads and located on the upper part of the frame require an equivalent alignment accuracy to the outer gimbal axis. These pads also receive an optical gage with optical pick-off faces which are parallel and perpendicular to both the gimbal axis and the star tracker mounting pads. The optical faces on the gage provide references for checking and alignment of spacecraft relative to the star tracker axes during installation.

Optical axis alignment is accomplished by the use of a master fixture with a mounting pad configuration similar to that of the star tracker. The master has a reflective face which is aligned to the planes formed by the pads to better than 2 arc sec and provides the basic reference for all subsequent alignment steps.

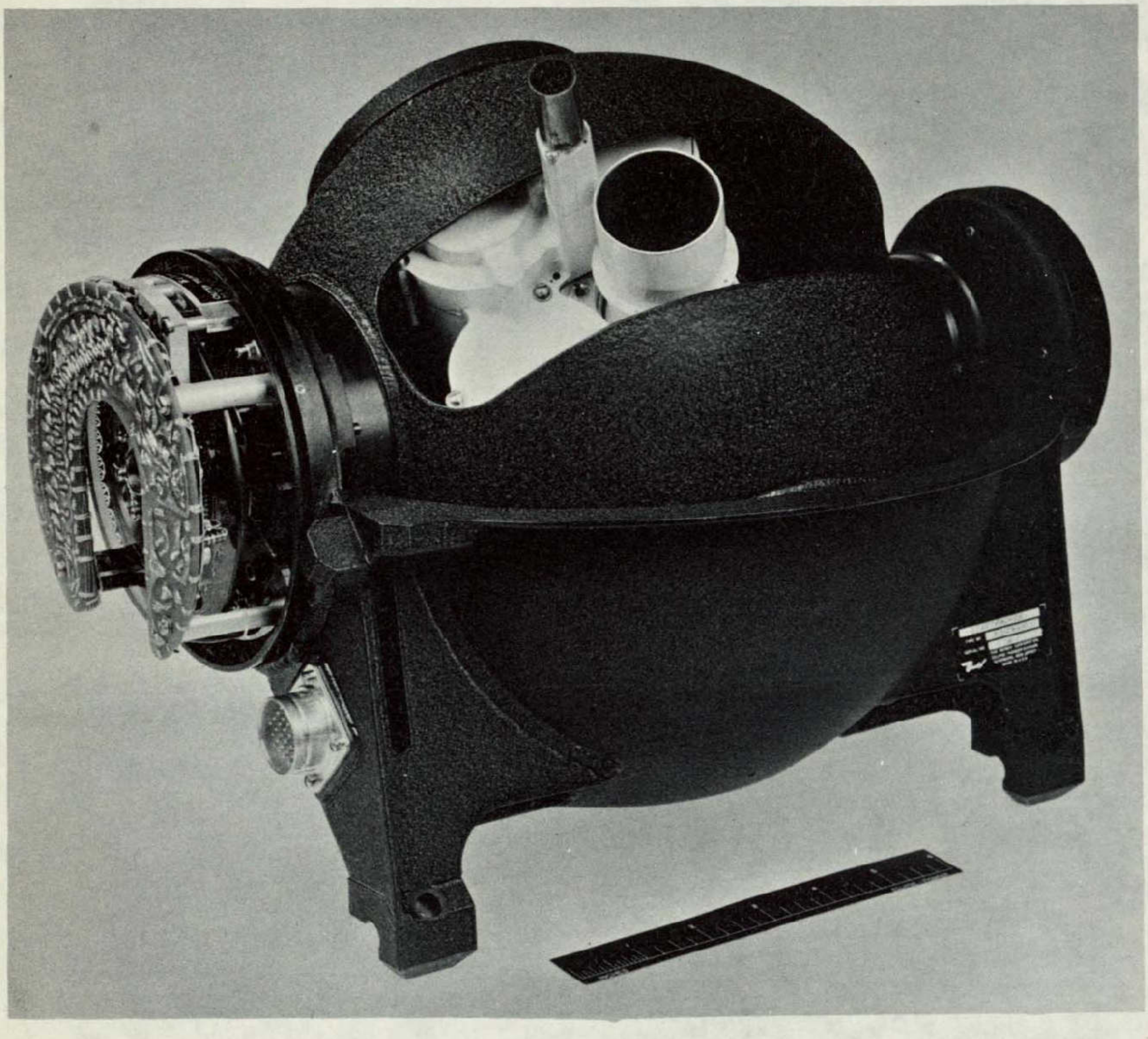
By use of the master reference and the optical pick-off on the rotational axes, the gimbals are adjusted and locked to their true zenith positions within 3 arc sec. The optical axis of the simulated star is aligned to its true zenith position within 3 arc sec.

3.2.9 Pictorial Display

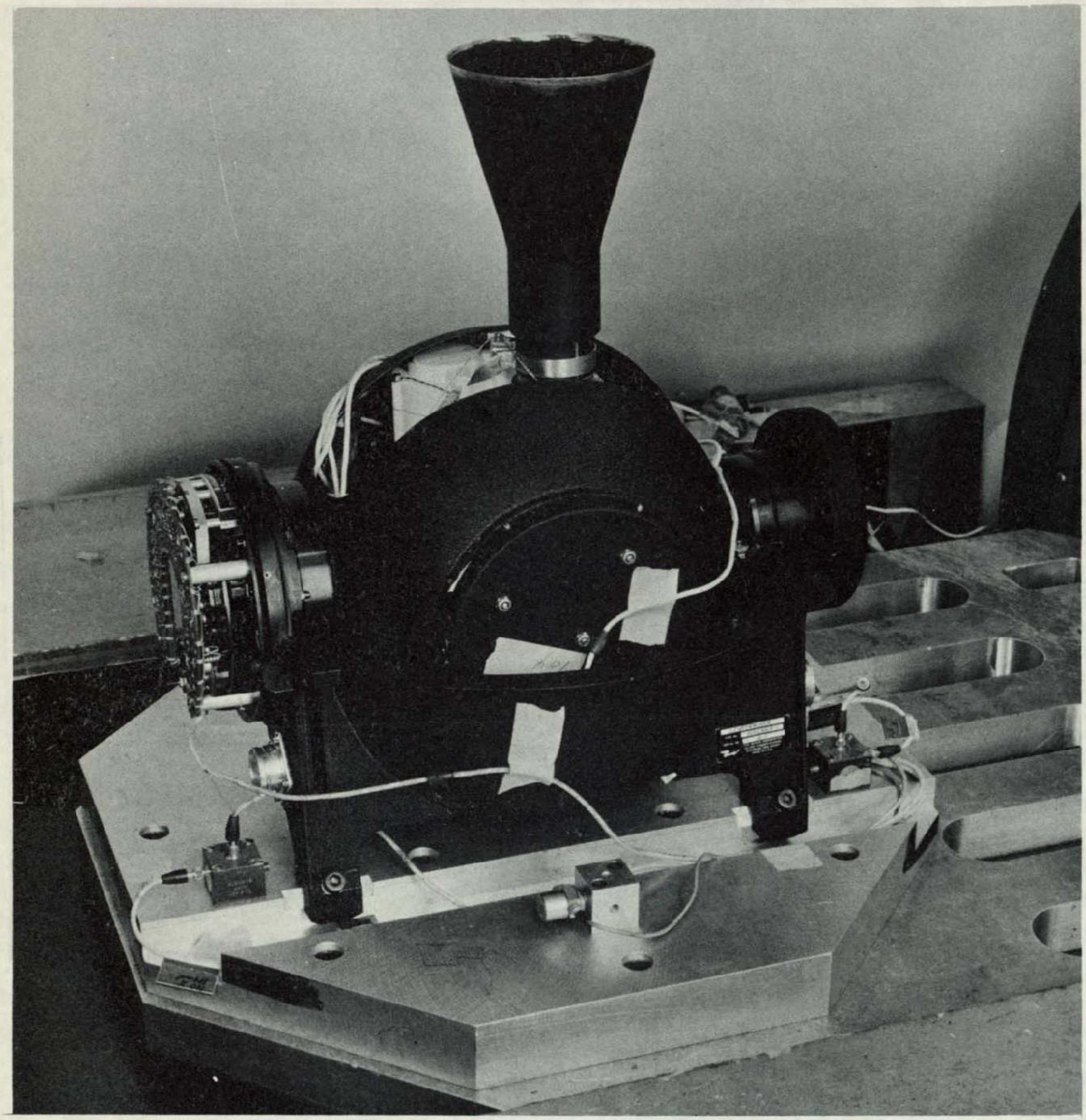
The photographs appearing on the following pages depict various sublevels of assembly of the early and latest models of the Bendix OAO Star Tracker.



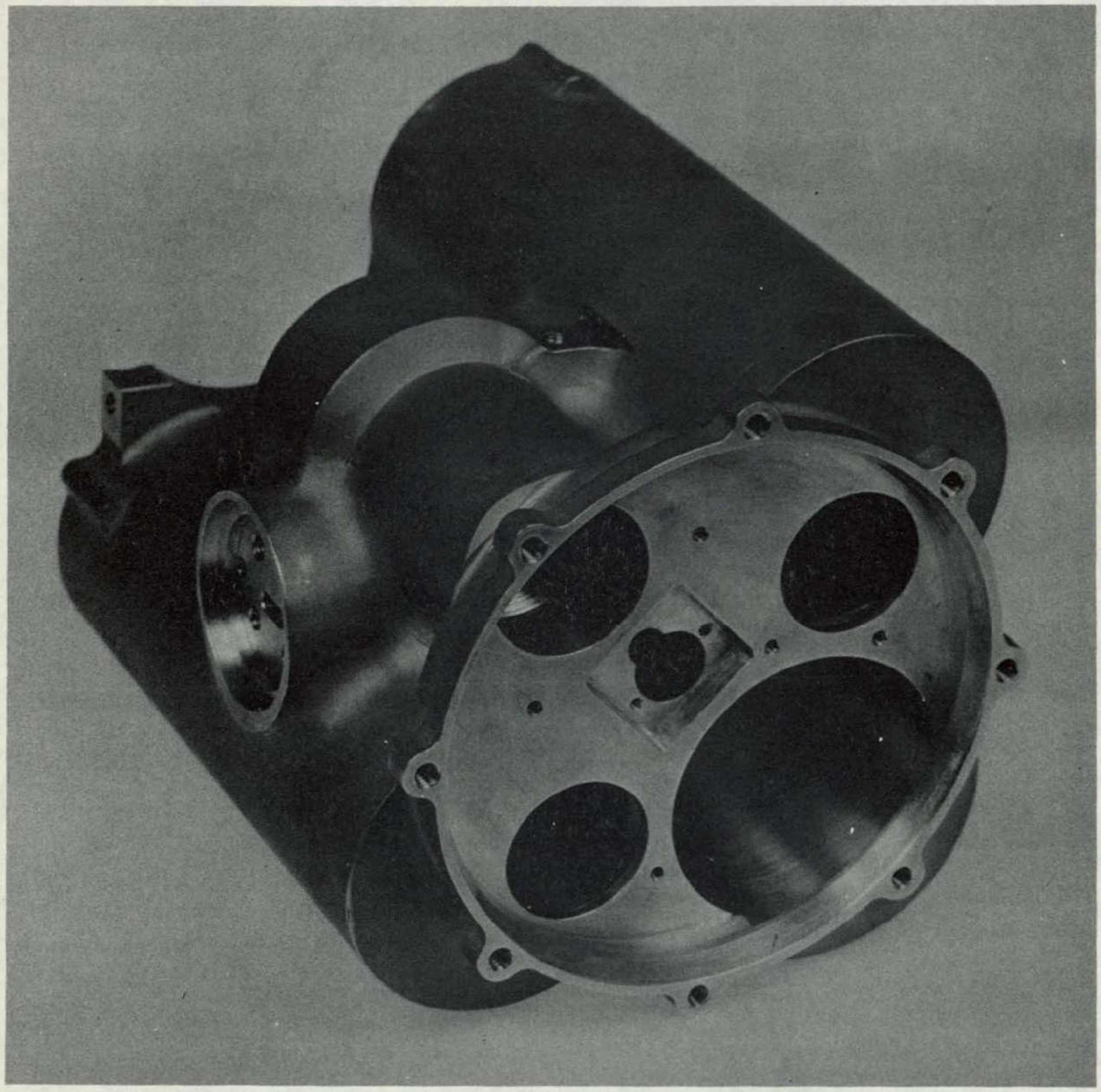
SPHERICAL GIMBAL
BENDIX OAO PROTOTYPE STAR TRACKER
FIGURE 3-3



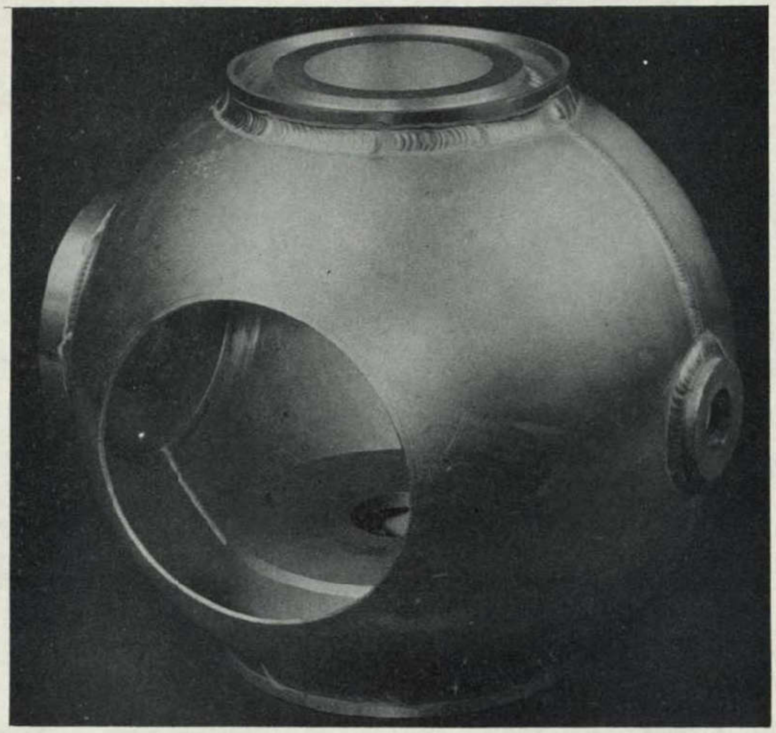
BENDIX OAO PROTOTYPE STAR TRACKER
FIGURE 3-4



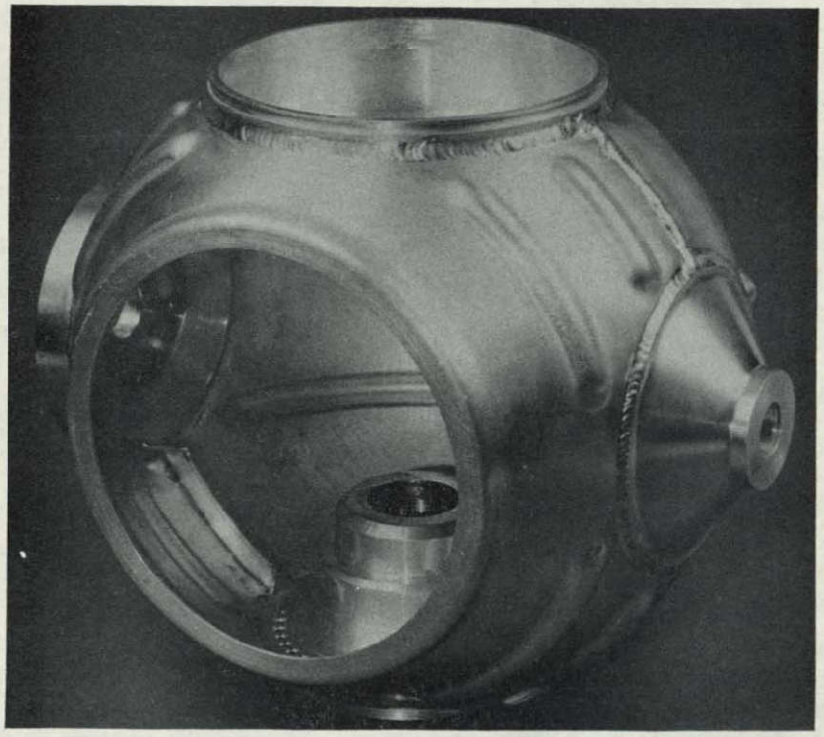
BENDIX OAO PROTYPTYE STAR TRACKER
FIGURE 3-5



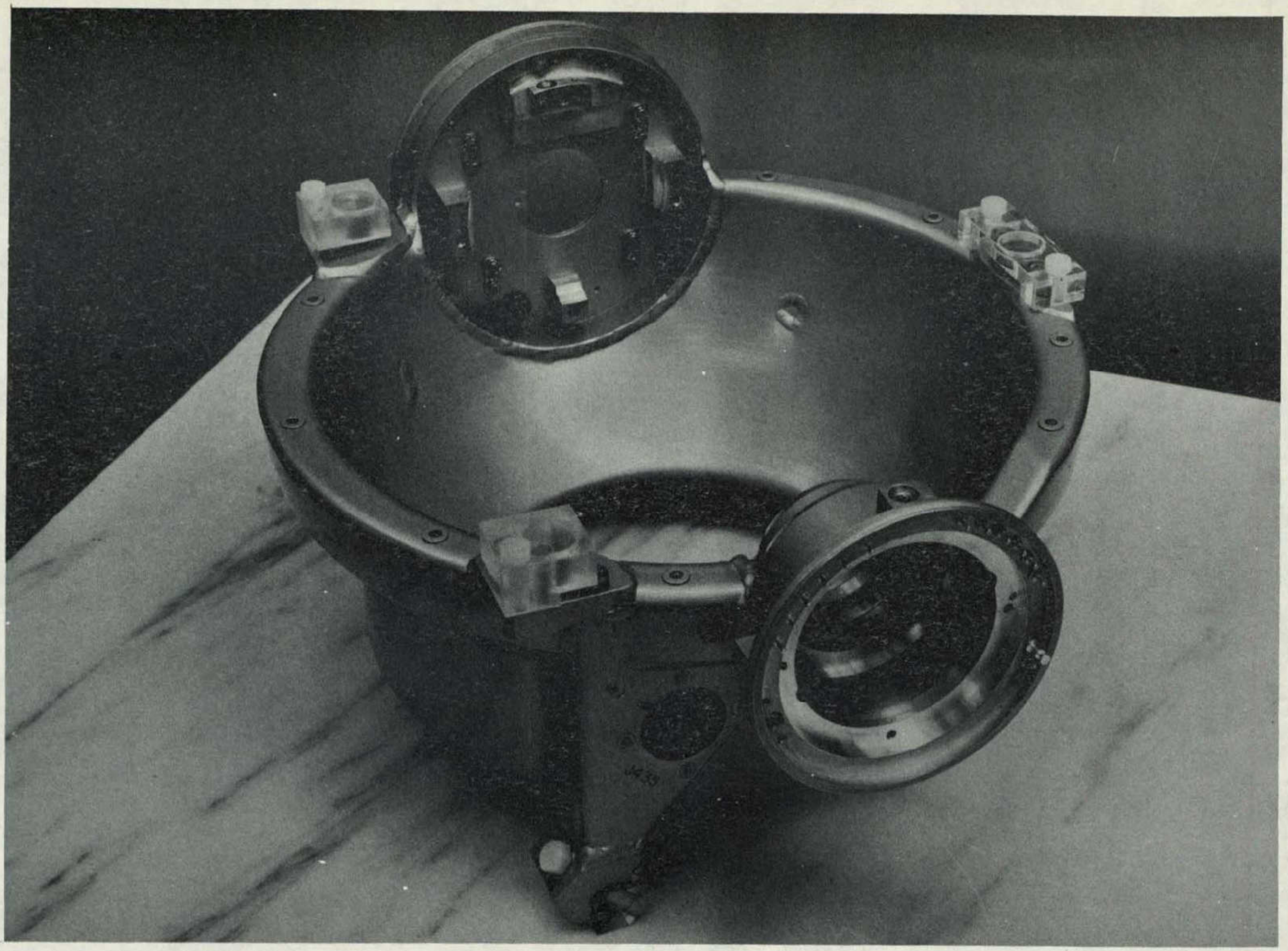
OAO TELESCOPE HOUSING
FIGURE 3-6



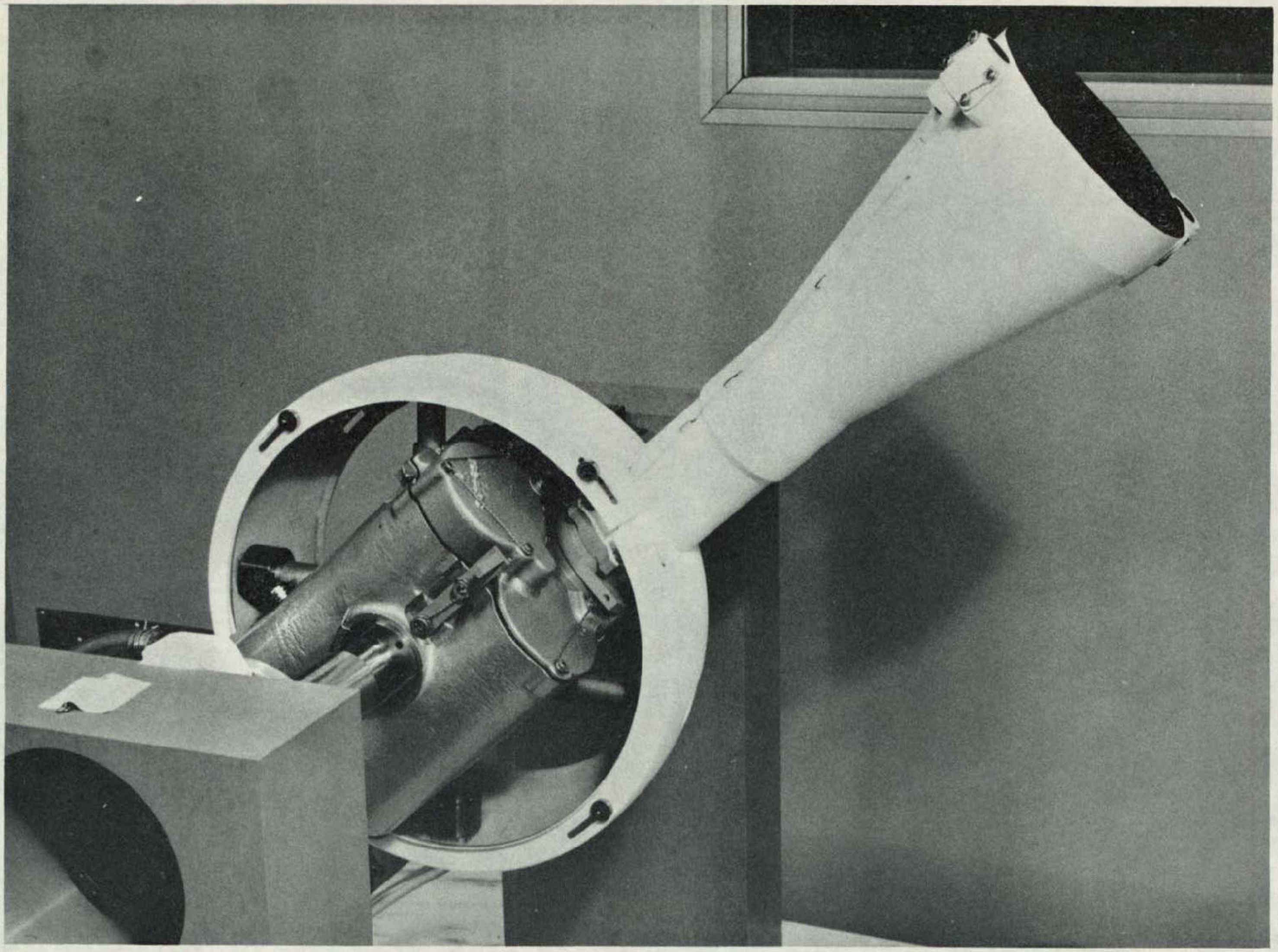
GIMBAL STRUCTURE



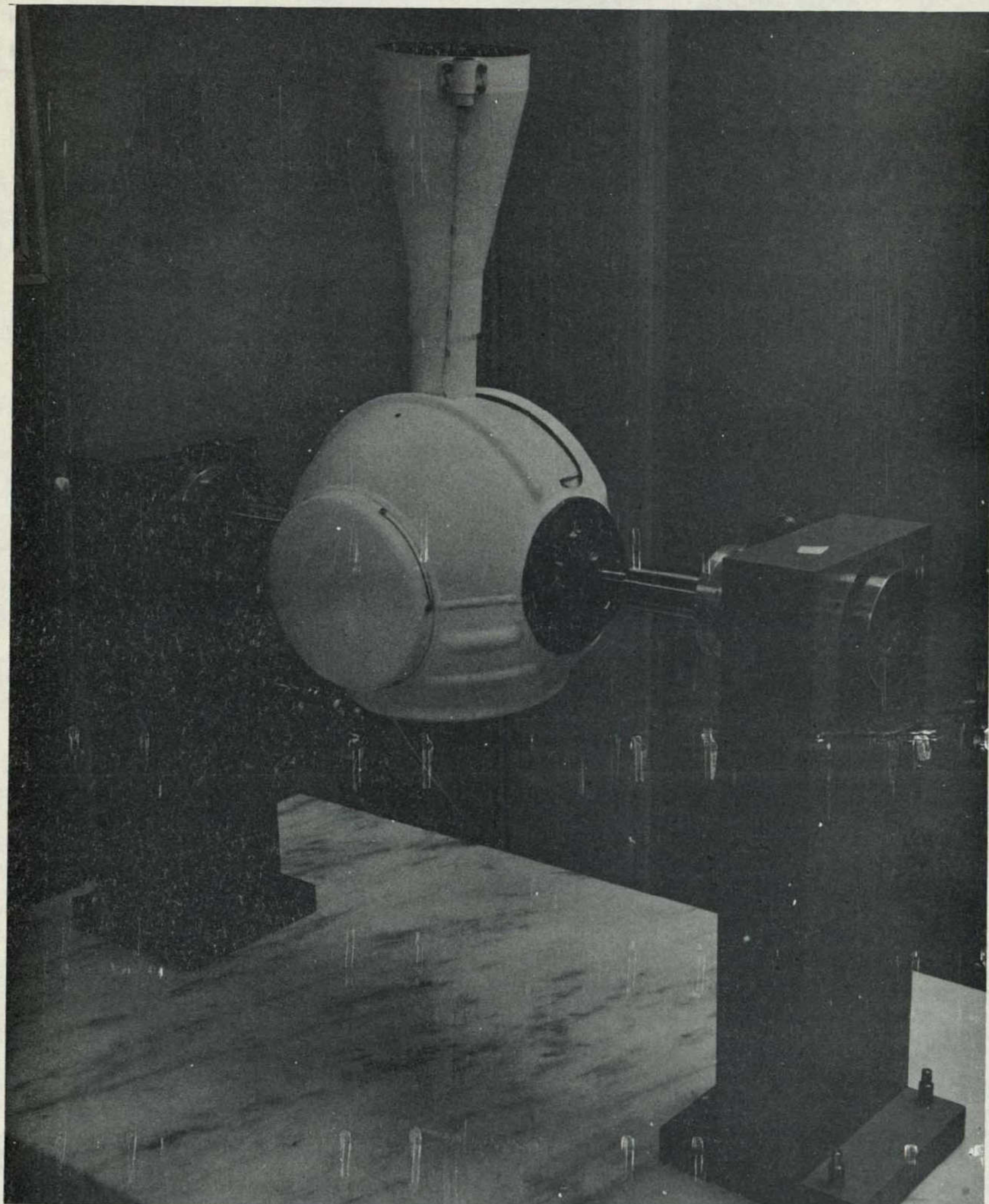
GIMBAL STRUCTURE
FIGURE 3-7



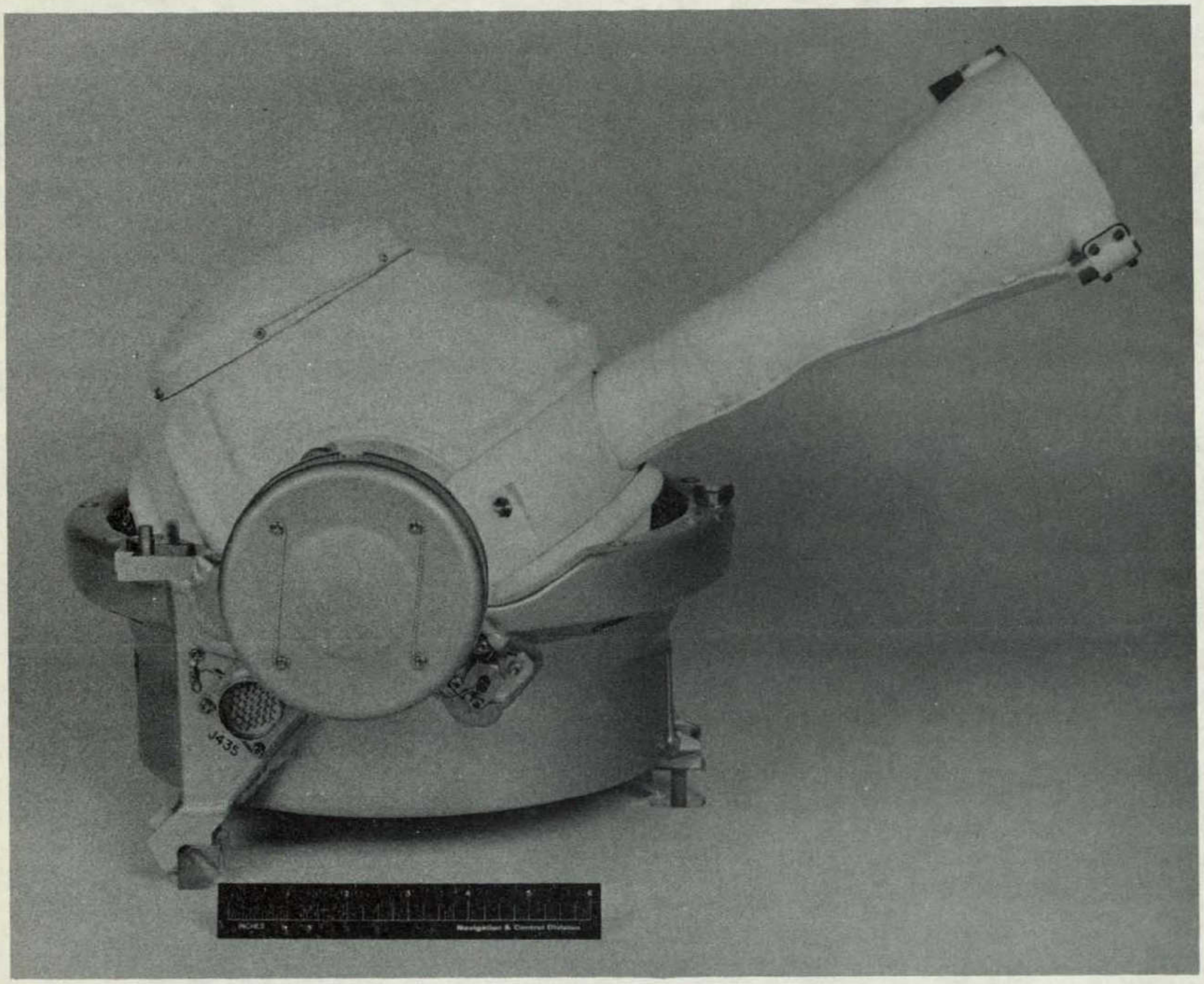
OMA FRAME ASSEMBLY
FIGURE 3-8



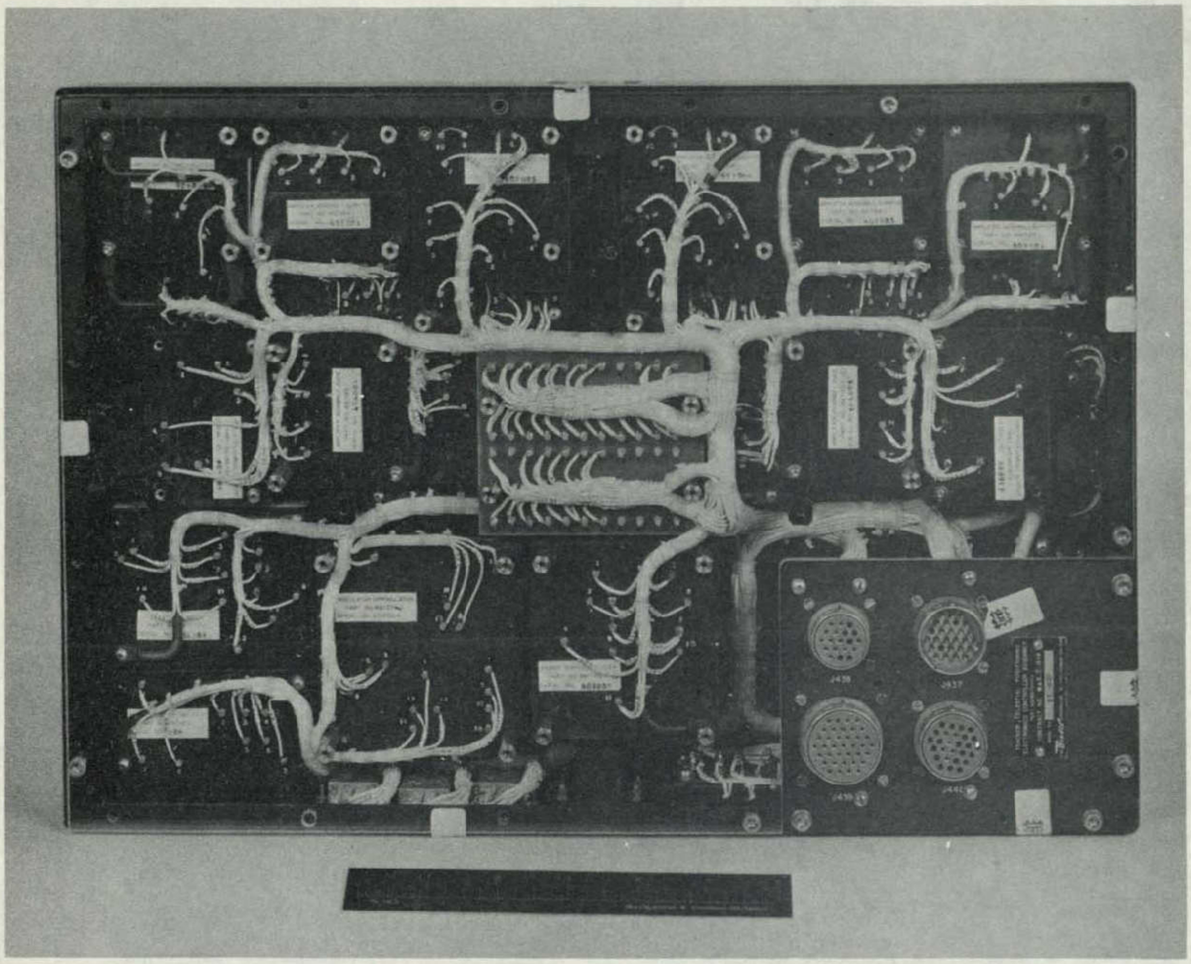
TELESCOPE SUBASSEMBLY
FIGURE 3-9



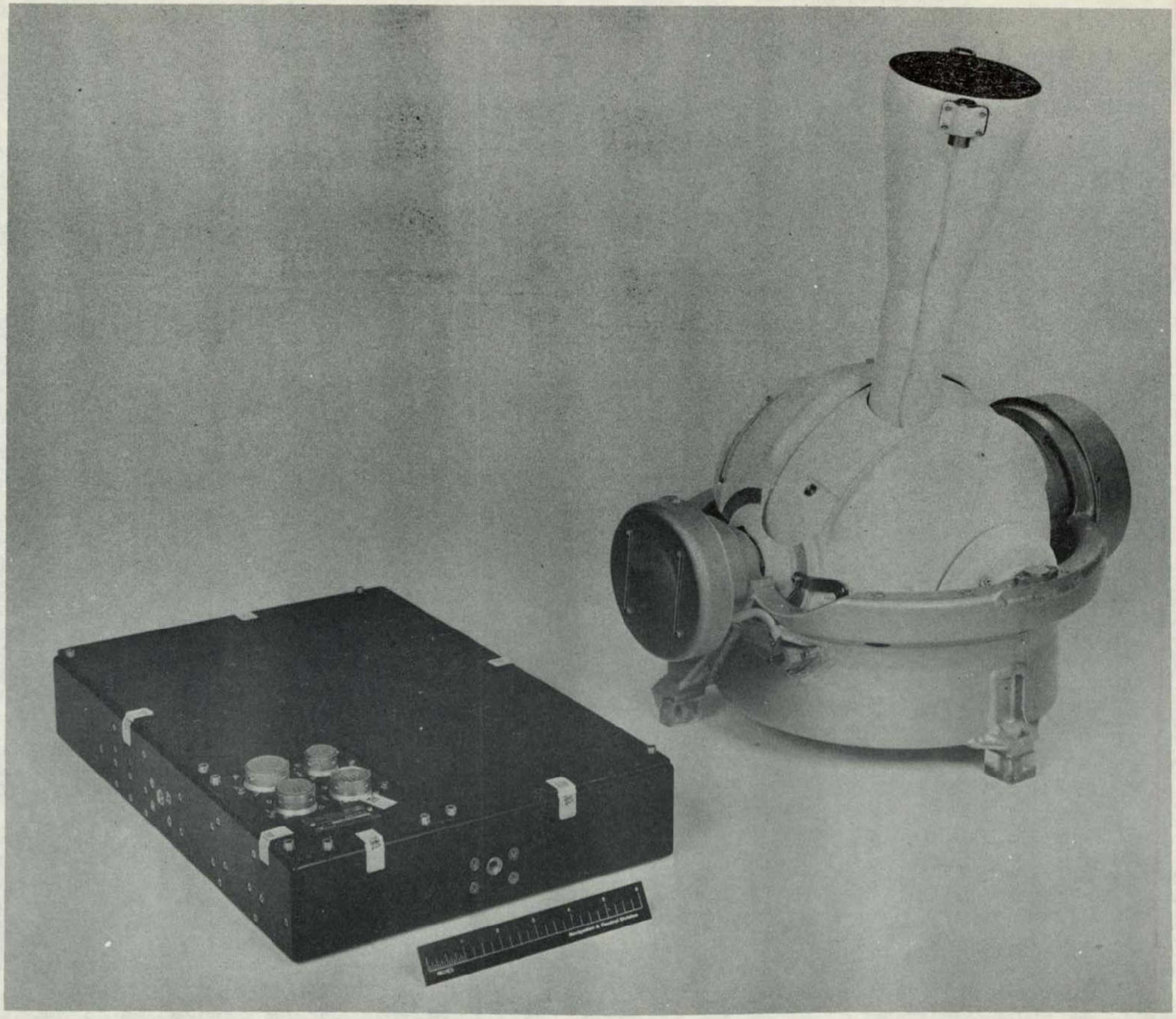
GIMBAL AND TELESCOPE ASSEMBLY
FIGURE 3-10



BENDIX OAO STAR TRACKER (OMA)
FIGURE 3-11



BENDIX STE SUBASSEMBLY
FIGURE 3-12



BENDIX OAO STAR TRACKER ASSEMBLY
FIGURE 3-13

4.0 RECOMMENDED DESIGN IMPROVEMENTS

A wealth of information and practical experience was acquired through Bendix involvement in the OAO Star Tracker Program. An extensive technical background was uniquely gained by association with the following:

1. A star tracker design and development period;
2. A four and one half month qualification test program performed in 1966-67;
3. An intensive technical investigation of problems uncovered during the qual test program;
4. The assembly of a second qualification star tracker incorporating in its design those solutions to problems uncovered during the first qual test program;
5. The performance in 1969 of a second four and one half month qualification test program.

If the assumption were made that Bendix were to be involved in a future OAO or similar gimballed star tracker program, then Bendix knowledge and experience could be applied in two immediate ways.

1. To improve the performance of the existing Bendix OAO gimballed star tracker through such design changes that the "Qualified" image of the tracker would remain somewhat intact, or
2. To modify the existing Bendix OAO gimballed star tracker incorporating in the design all previous knowledge gained through the OAO Program, and designing a new star tracker that would be more accurate and at the same time meet the requirements of a specification more stringent than OAO.

The contents that follow are to be considered recommended areas of design improvement. However, most of what follows have already been incorporated in other Bendix star tracker designs and therefore, have the value of being a design reality and not something in an idea stage in need of development. Also, some areas of improvement were partially accomplished for OAO but could not be completed due to the Grumman termination.

4.1 Telescope Assembly

1. Bendix-Designed Electronics

   Any new Bendix star tracker program similar in requirement to the OAO concept would utilize the already-designed, Bendix telescope electronics. The latter part of the OAO program had Bendix contractually authorized from Grumman to build and deliver production trackers using Bendix telescope electronics. Before termination, Bendix accomplished the following:

   - Detail design and layout package of the telescope assembly using mil-standard parts
   - Detail design and layout package of the telescope assembly using hi-rel parts
   - Prepared detailed procedures and specifications for all stages of module assembly and test

- Performed WCA for all modules and other analyses (noise, thermal) in support of the telescope operation
- Assembled and temperature tested all modules:
  - Photomultiplier
  - Hi-Voltage Power Supply
  - Video Amplifier
  - Demodulator
  - Track Sweep
- Interwired modules as telescope system and performed system tests over temperature

The tasks that remained, but could not be accomplished because of termination,were some circuit retailoring and retest over temperature, module potting, assembly of modules into telescope housing and telescope system tests in thermal vacuum. This work would have been completed in three weeks.

The Bendix-designed telescope electronics incorporated the experience and the solution to problems acquired with a vendor-supplied design for OAO. The Bendix design offers better stability of null over environments and includes protection against hi-voltage arc over making use of proven assembly techniques and special materials. The design also utilizes a deflectable photomultiplier tube manufactured to a Bendix developed hi-rel specification ensuring long tube life and protection against cracking glass due to environmental changes.

2. An area of immediate improvement would be to redesign the electronics using integrated circuits to reduce power drain and size. Schedule considerations did not permit this for OAO. Optimum use of I.C.'s has been accomplished in other recent Bendix star tracker programs. Such a redesign would allow updating components to present day standards. This redesign effort would use the same system gains and blocks as the qualified OAO star tracker to minimize problem areas.

3. Repackage the electronics in a more suitable manner to reduce interfacial wires within each module and improve the manner in which heat is removed from the modules.
4. Incorporate a connector on the telescope for anode current readout. This capability affords the opportunity for star magnitude calibration and cross checks and enhances overall test capability.

5. A design for a more stringent accuracy requirement would entail a concept already developed for other Bendix star tracker programs. A dual mode scan system whereby a small instantaneous field of view is scanned over a larger dynamic field.

In the coarse mode a raster-type scan pattern is used for star acquisition, while a cruciform pattern is used for fine mode or null. Signal-to-noise can be significantly increased using such a technique thereby improving system accuracy.

6. A new design would include HVPS regulation which would make a significant contribution to stability of null and consistency in star magnitude determination.

7. The addition of circuitry that would permit telemetry of star magnitude information. This was an initial requirement for the Grumman OAO contract and one in which Bendix proposed a design. The requirement was subsequently dropped due to schedule considerations.

8. A new design would incorporate a modular type assembly concept in which telescope module interconnection is accomplished mainly through connectors with a minimum amount of wiring. This consideration offers the means for faster assembly and ease of module replacement if the need arises.

9. Improve null stability over temperature by eliminating the prism in the OAO optical system. A current Bendix star tracker program has substituted a reflecting surface design in place of the prism.

The reflecting surfaces are part of the telescope mechanical structure. During OAO investigation large null shifts were attributed to the movement of the prism within its wobble plate cavity. Although this prism mount was redesigned for the second Qual test program and reductions in null shift were attained, analysis supports total elimination of the prism. Another important consideration is that the prism is extremely fragile and many prisms were cracked and destroyed due to improper contact during the OAO program.

4.2 OMA Assembly

1. A major problem experienced by Bendix during the Qual Test Program of 1966-67 was the outer gimbal bearing seizure that occurred after vibration. The intensive and thorough investigation that followed proved that the original bearing housing Hi-Shear coating breaks away from the housing and subsequently causes the seizure. The axes of the tracker were designed to have a floating bearing mount to compensate for gimbal motion as a result of thermal expansion. Hence this floating bearing mount causes the contact that eventually causes material flaking.

   A new material, hard anodized titanium, was the outcome of the investigation and this was incorporated into the design of the second Qual star tracker.

The results of the second Qual Test Program of 1969 were highly successful with an in-spec accuracy result after each environmental test performance.

Although this new bearing housing material has successfully withstood the present environmental requirements of OAO, more stringent vibration requirements would necessitate some changes in design. In a current Bendix star tracker program the floating bearing mount has given way to a locked bearing concept. In accomplishing this it was necessary to change the star tracker structural materials in order to match thermal coefficients of expansion. This material consideration solves the problem of gimbal motion brought about by thermal changes. This design greatly enhances the star tracker's capability to withstand a vibration level higher than OAO standards.

2. This same star tracker program uses solid cast, gimbal rings rather than the slotted, spherical gimbals of the OAO design. The rings are suitably ribbed to greatly extend the star tracker capability to withstand shock and vibration requirements in excess of OAO requirements.

3. The encoder assembly designed for this existing program has its own set of bearings and is connected to the OMA structure through a bellows arrangement. This concept, as analysis has shown, provides a good measure of stress relief by eliminating the solid mount concept of the OAO design. This design considerably reduces the possibility of OMA structural misalignments distorting the encoder mechanical mount. Any distortion of the encoder mount would bring about an encoder lamp defocusing which in turn would cause an encoder malfunction.

4. Improved accuracy would be gained by consideration of a more accurate encoder as the Baldwin 18 bit (5 arc second) and 19 bit (2.5 arc second) encoders as compared to the OAO designed 16 bit (20 arc second) encoder. Since the stated encoder accuracies would probably require a more favorable temperature range than that specified for OAO, some means of thermal control would be required in the design.

5. The OMA would be designed with ease and speed of assembly in mind. The present Bendix program uses the modular design concept throughout. For instance, a separate motor-tachometer pivot assembly and an encoder bearing assembly, can be assembled independent and in parallel with the OMA structural assembly. This concept also greatly facilitates replacement, if the need arises.

6. Designed into the OAO star tracker is a shutter mechanism activated by a sensor-trigger electronics assembly and used for photomultiplier cathode protection.

A number of malfunctions occurred in the trigger subassembly during the OAO program. In all cases the malfunctions were identical; a driver transistor became permanently shorted and activated the protective shutter. If such an incident occurred in space whereby a malfunction caused permanent activation of the shutter, the star tracker system would be rendered useless.

The trigger electronics operates off -28V DC and is a comparatively simple switching device with very few components. When the sensor output, which is a function of light input, reaches the required trigger voltage threshold, the shutter receives the -28V as an input and is subsequently activated.

In all cases of malfunction, investigation showed that the driver transistor of the network failed in the shorted mode. Except for one instance, all failures were traced to an inadvertent reversal of applied voltage to the trigger assembly thus destroying the transistor. In the one instance, the destroyed trigger was discovered after assembly and it was suspected that voltage reversal was unknowingly applied during subassembly testing. In order to protect against this type of mishap, a simple diode arrangement would be used in the future.

To protect against a failure mode that would cause permanent closing of the shutter during a space mission, a relay device would be incorporated as part of the trigger-shutter circuitry design. The relay would operate in such manner that a telemetry signal from earth would open the applied voltage line, thereby deactivating the protective shutter. The sensor output however, would have to be included as part of circuital information telemetered back to earth so as to be used to determine if a malfunction actually existed.

The ideas presented above offer a means of improving the reliability of the star tracker by slight modification of the existing shutter network design. However, in order to protect against all modes of failure, closed or open shutter, a complete redesign would be necessary.

4.3 STE Assembly

1. Servo Loop

   Redesign operational amplifiers using I.C.'s to improve performance and reduce power drain. The existing feedback networks would be maintained but some of the component types updated to reduce size. The redesigned op-amps would be tested to existing test specs to minimize the effect of this change on the overall qualified system.

2. Auxiliary Electronics
   Redesign using I.C.'s to reduce power and size where improvement could be achieved without major effort.

3. Explore the possibility of incorporating the STE electronics within the OMA structure thereby eliminating one of two packages and a group of cables. The reliability of the system would be increased, while the overall system weight decreased.